NASA TM-85659

NASA Technical Memorandum 85659

NASA-TM-85659 19830025573

# AN EVALUATION AND ASSESSMENT OF FLOW QUALITY IN SELECTED NASA WIND TUNNELS

W. D. Harvey, P. C. Stainback, and
F. K. Owen

AUGUST 1983



National Aeronautics and
Space Administration

**Langley Research Center**
Hampton, Virginia 23665

## INTRODUCTION

The boundary-layer transition process from laminar to fully turbulent flow is still not well understood, although the results of many years of research have provided a greater insight into the phenomena (ref. 1). The effect of flow disturbances on the transition process is of primary concern in wind-tunnel testing of scaled aircraft components. These disturbances may be composed of both turbulence and sound, the sources of each being a function of design details of the particular wind tunnel, and the relative disturbance level of each being related to gross and detailed features of the tunnel and flow speed. More recently an assessment of wind-tunnel flow quality and data accuracy requirements has been documented (ref. 2) and can be used to rank tunnels on the basis of the meaningful operating ranges of adequate flow quality relative to each proposed test program.

Since the validity of any ranking or judgment of flow quality is dependent upon measured quantities, it is important that we document the dynamic flow quality of the tunnels which are used for advanced aerodynamic testing. Spurred by the need for clearly defined low-turbulence-level flow quality to meet low drag airfoil testing requirements at the Langley and Ames Research Centers, NASA began an extensive program of wind-tunnel dynamic flow quality measurements and modifications in several transonic and supersonic facilities in the late seventies. It is the purpose of this paper to present recent experimental results from extensive and systematic studies of a number of NASA test facilities. The present paper will bring up to date the work that was initially reported in reference 3.

# SYMBOLS

| | |
|---|---|
| $\Delta C_p$ | $\tilde{p}/\bar{q}$ |
| $C_p$ | pressure coefficient |
| $c_f$ | skin-friction coefficient |
| e | voltage |
| K | screen resistance (pressure-drop)coefficient length |
| M | Mach number |
| n | number of screens |
| p | pressure |
| q | local dynamic pressure |
| $R_e$ | unit Reynolds number |
| u | velocity |
| x | axial distance or distance from wall slot origin |
| z | distance transverse to flow direction |
| $\Lambda$ | turbulence integral scale |

Subscripts:

| | |
|---|---|
| t | total conditions |
| u' | fluctuating velocity in streamwise direction |
| w' | fluctuating velocity in vertical direction |
| $\infty$ | free-stream |
| 1,2 | before and after, respectively |

Superscripts:

| | |
|---|---|
| $-$ | mean value |
| $\sim$ | rms value of fluctuating component |

## INSTRUMENTATION

For consistency, the measuring probes and dynamic recording instrumentation were identical insofar as possible in each of the facilities. Constant-temperature hot-wire anemometry techniques were used with probes having tungsten wires with $l/d \geq 50$. Individual wires were calibrated for the test range. Values of $\tilde{u}$ presented herein were reduced from simultaneous measurements of the mass-flow fluctuations ($\widetilde{\rho u}/\overline{\rho u}$) from the hot wires and pressure fluctuations from the acoustic probes, assuming negligible total-temperature fluctuations. Pressure transducers, cavity mounted within ogive-cylinder (acoustic) probes were used to measure the fluctuating static pressures. The pressure transducers and data-reduction methods were similar to those described in references 3 and 4.

## Facilities

Ames 2- by 2-Foot Transonic Pressure Tunnel (TPT). - A schematic of the Ames 2- by 2-Foot Transonic Pressure Tunnel is shown in figure 1 along with an indication (crossed circles) of the locations where measurements were made. The tunnel is a closed return, variable density facility with a two-foot square test section. It has an adjustable, flexible-wall nozzle and a slotted test section to permit transonic testing. The nozzle has a contraction ratio of 16:1 and there are no turbulence suppression screens or acoustic baffles in the settling chamber.

Hot-wire anemometers and pressure gages (cavity mounted within ogive cylinder probes) were used to measure the dynamic data in both the test section and settling chamber. Single (normal) and crossed hot-wire probes were used to determine the streamwise and lateral turbulence intensities, while the pressure gages measured the acoustic fields. Measurements were

obtained at Mach numbers between 0.6 and 1.4 over a Reynolds number range of 1 to 8 million per foot.

Langley Low-Turbulence Pressure Tunnel (LTPT). - The Langley Low-Turbulence Pressure Tunnel was designed especially for research on wing sections. A low-turbulence airstream was desired in which systematic investigations of large numbers of airfoils could be made at flight value Reynolds numbers. The tunnel (fig. 2) is of welded steel construction to permit operation at pressures up to 10 atmospheres. The test section is 3 feet wide, 7-1/2 feet high, and 7-1/2 feet long. The contraction ratio is 17.6:1.

Limited measurements of the tunnel turbulence were made in January 1940 before installation of the screens. After the installation of seven screens, hot-wire turbulence measurements were made on two occasions in 1941. These latter measurements showed a significant reduction in turbulence level; the levels being about 0.02 percent at low speed to a value of about 0.05 percent at a speed corresponding to a Reynolds number of about $4.5 \times 10^6$ per foot of model chord. However, over the past 40 years, there has been some damage to both the screens and cooler requiring replacement and or rehabilitation of these devices. The purpose of the present tests was to determine the vorticity and pressure fluctuations in the test section, upstream and downstream of the cooler, and the screens following the aforementioned modifications.

Once again, hot-wire anemometers and static pressure probes were used, the probes being sting mounted in the test section and on the tunnel centerline in the settling chamber ahead of the cooler, and upstream and downstream of the screens (fig. 2). Data were obtained up to a Mach number of 0.4 and a Reynolds number of 12 million per foot.

Langley 4- by 7-Meter Tunnel. - A sketch of the facility is shown in figure 3. This facility is a continuous-flow, closed-circuit tunnel with a contraction ratio of 9:1. There is a set of two screens at the inlet to the contraction. The Langley 4- by 7-Meter Tunnel (formerly V/STOL Tunnel, or Vertical/Short Take Off and Landing Tunnel) is used for testing powered helicopters and various commercial and military aircraft. It is powered by dual-drive motors which can provide precise tunnel speed control up to 200 knots with the Reynolds number per foot up to $0.195 \times 10^7$. The test section is 14.44 feet high, 21.65 feet wide and 49.88 feet long. The tunnel can be operated as a closed tunnel with slotted walls or as one or more open configurations by removing the side walls and ceiling to allow extra testing capabilities, such as flow visualization and acoustic tests. Furthermore, a moving-belt ground board with boundary-layer suction and variable-speed capabilities for operation at various test section flow velocities can be installed for ground effect tests. Both hot wire and acoustic probes were used to measure the flow quality around the entire circuit of the Langley 4- by 7-Meter Wind Tunnel as indicated by the circles with crosses in figure 3. Dynamic data were obtained in the test section, end of the first diffuser, before the vanes in the second diffuser, beginning of third diffuser ahead of the fan, end of fourth diffuser and across the settling chamber screens.

Ames High Reynolds Number Channel (HRC). - A schematic of the test section of the Ames High Reynolds Number Channel Number 1 (HRC 1) is shown in figure 4(a). Measurements in HRC 1 were made on the tunnel centerline, at the wall, and in the settling chamber. The facility is a blow-down tunnel and uses a large settling tank with various throttling plates and screens for conditioning the flow. For the present study, a test channel 9.84 inches wide, 14.96 inches high, and 59.1 inches long was used. The test section Mach number was regulated by choking the flow downstream of the test section by

using inserts on the top and bottom walls. Data were obtained at free-stream Mach numbers of 0.4, 0.6, and 0.8 for unit Reynolds numbers up to 40 million per foot. The measurements were made before and after the flow conditioning tank was modified by the installation of an array of noise suppression panels and a honeycomb section (fig. 4(b)).

The second test channel, HRC 2, is shown in figure 5. The settling tank is designed for operation up to 200 psi. In the present test program, tunnel flow quality measurements were made at tunnel total pressures up to 60 psia at free-stream Mach numbers of 0.6, 0.7, and 0.8. Data were obtained with and without sidewall boundary layer removal (fig. 5).

Hot wire and hot film anemometers and three types of pressure probes were used to measure the dynamic data. Two pressure probes were designed to measure the static and total pressure fluctuations. The static pressure probe consisted of a pressure gage cavity mounted within an ogive-cylinder. The total pressure probe consisted of a diaphram covered pressure gage mounted at the nose of a pitot tube. The third type probes were cavity mounted and measured sidewall pressure fluctuations in the test section and settling chamber. Originally, both hot wire and hot film probes were used to measure the axial turbulence levels since it was anticipated that, particularly at high Reynolds numbers, the hot wire probes would not withstand the large aerodynamic loads. This turned out not to be the case. However, in the modified HRC 1 some problems with wire breakage were encountered. For this reason, film probes were used for the turbulence measurements since good agreement between these probes and conventional hot wire probes was demonstrated in the previous tests.

## RESULTS AND DISCUSSION

### Fluctuating Amplitudes in the Test Section

Hot-wire turbulence and free-stream pressure fluctuations obtained in the Ames 2- by 2-Foot TPT are shown in figures 6 and 7. For constant Mach numbers, the data show consistent trends of increasing turbulence levels with increasing unit Reynolds number, i.e., increasing tunnel power level. However, the rate of increase is considerably greater for the supersonic flow results ($M_\infty \geq 1.2$). The high disturbance level results at subsonic speeds and at low Reynolds numbers are believed to be due to large-scale flow unsteadiness produced by the tunnel drive system. For constant Reynolds number and subsonic Mach numbers, turbulence levels (fig. 6) increase for a given Mach number. Supersonically there is an initial reduction due to choking downstream of the test section which blocks diffuser disturbances from propagating upstream in the test section. However, as Mach number is further increased, particularly at the higher Reynolds numbers, the turbulence levels once again increase, the result primarily of increasing power levels and possibly increasing radiation from the turbulent boundary layer on the tunnel side walls. Transverse velocity fluctuations were also measured in the test section with crossed wire probes. These measurements, when ratioed by the corresponding axial turbulence levels of figure 6, show that the transverse levels are generally higher ($\approx$ 10 percent) as would be expected from vortex stretching through the contraction.

The test section static pressure fluctuation measurements in the Ames 2- by 2-Ft. TPT are shown in figure 7. Since typical fluctuating pressure coefficients, defined as $\Delta C_p = (\tilde{p}/\bar{q}) \times 100$ percent, may range from 0.5 to 5.0 depending on tunnel configuration, it can be seen that the facility performs well at high Reynolds number over the entire Mach number range. At low dynamic pressures the contribution of wind-tunnel tones accounts for the rapid rise in the

fluctuating pressure coefficients. Assuming that the pressure fluctuations are plane and unidirectional, the root mean-square turbulence level can be calculated from the relationship $\tilde{u}/\bar{u} = \tilde{p}/\gamma\bar{p}M$. These calculations were made for several ranges of constant total pressure and show that the measured pressure fluctuations could make a significant contribution to the measured turbulent velocity fluctuations depending upon speed and $\Delta C_p$ level.

Representative free-stream velocity and static-pressure fluctuation levels in the Ames HRC 1 and 2 are shown in figures 8 and 9. The variation in trend of measured $\tilde{u}/\bar{u}$ with total pressure (fig. 8) or $\tilde{p}/\bar{q}$ with $M_\infty$ (fig. 9) for either HRC 1 and HRC 2 is as expected. For HRC 1, the measured disturbance levels (figs. 8 and 9) before modification (fig. 4(b)) were significantly reduced as indicated by the after modification results. However, as illustrated in figure 4(b) there remains a rather sharp corner downstream of the last screen between the settling tank and bellmouth entrance cone that can introduce unsteady or separated flow disturbances into the contraction and test section. The inlet valve and perforated pipe (fig. 4(b)) may further influence the honeycomb and screen performance (ref. 5). Although blow-down facilities are inherently noisy, it can be seen that, with suitable management, acceptable flow quality can be achieved.

In low-speed tunnels, pressure fluctuations are generally small and the primary disturbance source is vorticity fluctuations. However, a comparison between test section turbulence levels in the Langley LTPT and 4- by 7-Meter Tunnels (fig. 10), shows that large ranges of flow quality level are clearly evident, i.e., the Langley 4- by 7-Meter Tunnel level is about an order-of-magnitude higher than the Langley LTPT. The major difference between the Langley LTPT and 4- by 7-Meter Tunnel results is attributed to unsteady flow development in the first diffuser of the 4- by 7-Meter Tunnel followed by separation in the second and third diffuser with subsequent side loading of the fan (ref. 6).

This will produce high level, low frequency disturbances that traverse the tunnel circuit. These results will be subsequently discussed.

## Spectra Measured in Test Section

Not only do fluctuation amplitudes affect model performance, but spectral characteristics are also important. Therefore, spectra measurements were obtained and attempts were made to gain a better understanding of the disturbance environment and sources in each facility. For the Ames 2- by 2-Ft. TPT, representative variations of the broad-band energy spectra from hot-wire and static-pressure probes are presented in figure 11 and show several flow features. Over the Reynolds number range tested there is, as expected, an increased high frequency, (small scale) contribution with increasing unit Reynolds number. The hot-wire spectra also show significant energy peaks which become more pronounced with increasing tunnel power level. It is apparent, by comparisons of the hot wire with the free-stream static pressure probe data (fig. 11), that these peaks are acoustic tones. An inspection of the settling chamber spectra show that these tones propagate around the entire wind-tunnel circuit. They are present at all Mach numbers, and perhaps most clearly defined for $M_\infty = 0.8$ at $R_e = 8$ million/ft. (fig. 11), although their exact source cannot be determined from the present measurements.

In Ames HRC 1, the energy spectra in figure 12 corresponding to the free-stream pressure data (fig. 9) show that there is, as expected, an increased high frequency of small scale contribution to the total turbulent field with both increasing Mach number and unit Reynolds number. The energy content (fig. 12), however, was found to be predominantly large scale since relative magnitudes were down several orders of magnitude at the higher frequencies. This rapid decay of energy with frequency is typical of most types of wind tunnels. It was apparent, from comparisons with other wind-tunnel free-stream spectra, that the reductions in test section RMS levels of the Ames HRC 1 can

be attributed to reduced higher frequency (small scale) contributions to the total turbulent and acoustic fields.

Measurements in the low-speed facilities confirm that large-scale, low frequency vorticity fluctuations are the primary test section disturbances. Estimates of the integral length scales around the Langley 4- by 7-Meter Tunnel circuit for a dynamic pressure of 30 psf have been made using area ratios at each station to estimate local mean velocity. This simple calculation indicated that the axial length scales upstream of the settling chamber screens are about 6 feet, less than 2 feet at Station 19, and less than 3 feet in the test section (fig. 3) due to vortex stretching. In the diffuser and at Station 10, the scales increase to almost 12 feet. They are 4 feet behind the second corner catcher screen and almost 6 feet after the fan nacelle. These preliminary estimates show that the dominant turbulence inputs are large-scale fluctuations generated in the diffuser and to a lesser extent across the fan. As expected, principal scale reductions occur across the settling chamber and catcher screens.

## Pressure Fluctuations

It has been found that the most intense sound waves at the higher Mach numbers are those moving upstream. This has been confirmed by cross-correlation measurements in the Langley 8-Foot Transonic Pressure Tunnel (8-Ft. TPT) (ref. 3). For example, the distances between transducers in the tunnels were sufficient to make the correlations of vorticity negligibly small. Thus, correlations of the acoustic modes can be measured directly. At Mach numbers below 0.8, and with the output of the probe in the Langley 8-Ft. TPT diffuser (ref. 3) delayed, it was determined that there were coherent acoustic disturbances which propagated upstream into the test section from the diffuser. The propagation speed, determined from the spatial separation and time delay for optimum correlation, was approximately equal to the speed of sound minus the free-stream velocity.

When sonic flow existed over the area of the test section, all correlation disappeared since weak pressure waves moving upstream cannot propagate forward in sonic or supersonic flow. Thus, under these conditions, response of the transducers are only to pressure waves moving downstream and to noise radiated from the turbulent boundary layers on the tunnel walls ahead of the probe.

Although it was apparent from the energy spectra that some acoustic disturbances propagate around the entire Ames 2- by 2-Ft. TPT circuit, noise levels in the test section are still substantially reduced for $M_\infty \gtrsim 0.8$ once choking occurs downstream (fig. 13). Thus, installation of carefully designed sonic throats between the test section and diffuser could significantly improve flow quality in these facilities. This approach has been employed in the Langley 8-Ft. TPT (ref. 3).

In the present blowdown facilities, the major sources of flow fluctuations probably originate at the valve upstream of the settling chamber and in the settling chamber (ref. 5). Measurements of the Ames High Reynolds Number Channels (HRC 1 and 2) show that, despite flow control chokes which prevent diffuser generated fluctuations from propagating upstream, test section noise levels and turbulence were high. However, the installation of acoustic baffles and honeycomb in the HRC 1 settling chamber have greatly improved flow quality (figs. 8 and 9). The pressure fluctuation results for the modified

channel are compared with similar measurements obtained in other transonic facilities in figure 14. Although HRC 1 is an inherently noisier blowdown facility, while the other facilities have continuous circuits, the modified HRC 1 levels are now comparable to other facilities at Mach 0.6 and lower than most at Mach 0.8. These results confirm the importance of flow quality documentation and the detection and treatment of the sources of poor flow quality. To increase settling chamber volume and length is usually a compromise between cost of material and space. However, the new HRC 2

facility, built with a relatively larger settling chamber, shows that compromises towards larger settling chambers are worthwhile. The first flow quality measurements obtained without settling chamber flow treatment indicate that modifications similar to those in HRC 1 would produce a high Reynolds number test facility with relatively good flow quality.

## SETTLING CHAMBER MEASUREMENTS

Hot-wire measurements were made in the settling chamber of the LTPT Tunnel. Figure 15 shows that there is a significant turbulence reduction across the cooler together with reduction of the integral scales. Figures 16 and 17 show the turbulence reduction as the flow passes through the new settling chamber screens and contraction resulting in test section turbulence levels of less than 0.1 percent. The indicated reduction ratio of 30 to 40 across the screens over the range of Reynolds number shown in figure 16 is considered excellent.

Settling chamber hot-wire fluctuations are shown in figure 18 for the Ames 2- by 2-Ft. TPT. Although no specific Mach number effects are apparent, they do follow the trends observed in the test section, i.e., increasing turbulence and decreasing normalized pressure fluctuation levels with increased unit Reynolds number. Figure 18 shows that the turbulence levels ahead of the contraction are significant, varying from 2 to 6 percent. These levels suggest an obvious improvement that could be made to flow quality, namely the installation of screens and honeycomb in the settling chamber.

The study of the Langley 4- by 7-Meter Tunnel, in which measurements were obtained around the entire circuit, revealed that the diffuser is the primary cause of unsatisfactory flow quality in the test section. These results are further supported by mean-flow measurements presented in reference 6. The measurements of turbulence level (fig. 19) and spectra show that the source of the diffuser disturbances are large-scale unsteadiness and intermittent flow separation. These disturbances are then convected around the tunnel

circuit with additional input from the fan and from flow separations around the third and fourth corners. Although screen performance is satisfactory, contraction performance is much lower than area ratio predictions, which has been the case in other tunnels. It is clear that each element of the tunnel circuit needs improvement with priority given to the diffuser flow and the separations after the fan.

The effectiveness of screens for flow-quality management has also been assessed. In the Langley 4- by 7-Meter Tunnel, measurements upstream and downstream of the screens have been made. It can be seen in figure 20 that upstream of the screens the axial velocity scales are about twice the vertical velocity scales. However, downstream, the screens have greatly reduced the axial scales. This relative reduction increases with tunnel power, i.e., pressure drop across the screens. Figure 21 shows the details behind this observation; namely, that the vertical velocity scales are essentially unaffected by passage through the screens, whereas, the axial fluctuation scales are greatly reduced. Also, as expected, the transverse fluctations are relatively unaffected by passage through the screens.

Screen efficiency calculations have also been made and are presented in figure 22. These results show that the Langley LTPT (9 screens) and 4- by 7-Meter Tunnel (2 screens) performance is satisfactory, while the Ames 12-Foot Pressure Wind Tunnel (12-Ft. PWT) (ref. 3) (8 screens) is not. This comparison clearly shows the degraded performance of the screens in the Ames 12-Ft. PWT. There are two possible causes of this poor screen efficiency, namely, mean flow nonuniformity ahead of the screens and too high solidity of the screens. If the mean velocity has nonuniformities of only a few percent, regeneration of turbulence can occur through a screen and screen efficiency is reduced. Such nonuniformities could possibly be produced in the Ames 12-Foot PWT by unsteady flow separations downstream of the sudden expansion ahead of the screens. These separations

were evident from the hot-wire spectra data ahead of the screens, particularly at high dynamic pressures. It would be more efficient to manage existing large-scale unsteady motions ahead of the screens. This would lead to improved screen efficiency, lower settling-chamber turbulence levels, and consequently even lower values in the test section. Based on results from earlier experience with turbulence suppression devices, analysis suggests that the Ames tunnel screens may have a solidity that is too high (refs. 7 - 9). Decreasing the solidity could also reduce the test-section turbulence. Inspection shows that dirt build-up has probably decreased porosity to such an extent that the eight screens produce a turbulence reduction closer to that predicted for a single denser screen rather than eight in series. This comparison indicates that turbulence reduction of up to a factor of five is possible by refurbishing the screens. No tunnel is absolutely free from dirt and its accumulation on the screen wires increases their solidity. Thus, dirt not only effects pressure drop but also the refractive properties of the screen. This latter effect can produce small but significant free-stream axial vorticity. Fig. 23 (ref. 10) shows the spanwise skin-friction distribution in the RAE 4.5- by 4-Foot Tunnel working section before and after cleaning one screen. It can be seen that the peak-to-peak variation about the mean was reduced from about 16 to 6 percent. The variation was caused by the presence of longitudinal vortices formed by coalescing jets from the screen pores. Other spanwise nonuniformities have also been observed; for instance, two hot-wire turbulence surveys across the test section of the Ames 2- by 2-Foot Tunnel (fig. 24) for different overheat ratios, show obvious increases as the side walls are approached. Note the significant increases off the centerline which can be traced to turbulence wakes generated by a survey tube

holder located upstream in the settling chamber. It is important that the full potential of our existing facilities be utilized by adequate maintenance and flow quality awareness.

An assessment has also been made of the longitudinal turbulence transmissibility through the contractions. Figure 25 shows the effect of nozzle contraction on turbulence transmitted compared with theory (ref. 11). This comparison indicates that there is a significant difference in level and trend with Mach number for a given contraction ratio. Figure 25 shows that the theoretical predicted turbulence-reduction factor decreases with increasing Mach number. However, the measured values increase with subsonic Mach number in the wind tunnels tested. But all the nozzle contraction data are contaminated by sound at transonic speeds, which can influence the aforementioned effects. At low speed, where the contribution of sound to the overall hot-wire measurements is small, contraction ratio performance can be estimated by simple area ratio considerations. There appears to be no measurable effect of damping due to vortex modification through the contractions. At high subsonic Mach numbers, the increased contribution of pressure fluctuations to the test section hot-wire measurements account for the apparently degraded performance in the transonic regime. Spatial turbulence variations across the settling chambers further compound the problem, turning vanes are a primary source of spanwise turbulence intensity and scale variations.

## CONCLUDING REMARKS

Tests have been conducted in five facilities at the NASA Langley and Ames Research Centers to measure characteristic disturbance levels and spectra in their respective settling chambers and test sections, and to determine the sources of these disturbances. The primary conclusions are as follows:

It has been demonstrated in the past that significant reduction of the disturbance levels in transonic facilities could be affected by introducing a properly designed sonic choke devices downstream of the test section but upstream of the strut and diffuser. Thus, the only remaining test-section disturbances would be noise radiated from the turbulent boundary layer at the test section wall and relatively low-level pressure fluctuations, vorticity, and entropy fluctuations convected from the settling chamber. The installation in or upstream of the settling chamber of carefully selected screens, honeycomb, and acoustic baffles could further reduce test-section turbulence levels and scale without substantial pressure losses. This was dramatically demonstrated for the Ames High Reynolds Number Channel (HRC 1 and 2) blow-down type of facilities.

The Langley LTPT coolers perform somewhat like honeycomb-screen combinations. However, further large reduction of the settling chamber disturbance levels was obtained by the installation of properly selected screens in the settling chamber.

The study of the Langley 4- by 7-Meter Tunnel, in which measurements were obtained around the entire circuit, revealed that the diffuser is the primary cause of unsatisfactory flow quality in the test section. The measurements show that the source of the diffuser disturbances are large-scale unsteadiness and intermittent flow separation. This is further influenced by the shedding of vortices at the nozzle exit and their impingement on the diffuser collector

lip in the open test-section configuration. These disturbances are then convected around the tunnel circuit with additional input from the fan and from flow separations around the third and fourth corners. It is clear that the flow quality in each element of the tunnel circuit could be improved particularly that in the diffuser and after the fan.

In the NASA Ames blowdown facilities, the major source of flow fluctuations originates at the inlet valve and in the settling chamber. However, despite the fact that these facilities are inherently noisier than continuous, closed-circuit facilities, the present work shows that acceptable flow quality can still be achieved by settling chamber flow-management devices.

## REFERENCES


1. Recent Development in Boundary Layer Transition Study Group. Preprints of Articles in AIAA Journal, Vol. 3, No. 3, March 1975, based on Papers Presented at AIAA 12th Aerospace Science Meeting, February 1975.

2. Steinle, F. and Stanewsky, E.: Wind-Tunnel Flow Quality and Data Accuracy Requirements. AGARD Report 184, Edited by R. O. Dietz, 1983.

3. Harvey, W. D.; Stainback, P. C.; and Owen, F. K.: Evaluation of Flow Quality in Two Large NASA Wind Tunnels at Transonic Speeds. NASA TP1737, Dec. 1980.

4. Rose, William C. and McDaid, Edward P.: Turbulence Measurements in Transonic Flow. Proceedings from the AIAA 9th Aerodynamic Testing Conference, June 1976, pp. 267-271.

5. Anders, J. B.; Stainback, P. C., Keefe, L. R., and Beckwith, I.E.. Fluctuating Disturbances in a Mach 5 Wind Tunnel. AIAA Journal, Vol. 15, No. 8, Aug. 1977, pp. 1123-1129.

6. Applin, Zachary T.: Flow Improvements in the Circuit of the NASA Langley 4- by 7-Meter Tunnel. NASA TM 85662, 1983.

7. Scheiman, James; and Brooks, J. D.: A Comparison of Experimental and Theoretical Turbulence Reduction From Screens, Honeycomb and Honeycomb-Screen Combinations. A Collection of Technical Papers - AIAA 11th Aerodynamic Testing Conference, March 1980, pp. 129-134. (Available as AIAA-80-0433.)

8. Bradshaw, P.: The Effect of Wind Tunnel Screens on "Two-Dimensional" Boundary Layers. NPL Aero Rep. 1085, British A.R.C., Dec. 4, 1963.

9. Schubauer, G. B.; Spangenberg, W. G.; and Klebanoff, P. S.: Aerodynamic Characteristics of Damping Screens. NACA TN 2001, 1950.

10. Mehta, R. D.: Aspects of the Design and Performance of Blower Tunnel Components. Ph.D. Thesis, Imperial College London, Nov. 1978.

11. Uberoi, Mahinder S.: Effect of Wind-Tunnel Contraction on Free-Stream Turbulence. J. Aeronaut. Sci., Vol. 23, No. 8, Aug. 1956, pp. 754-764.

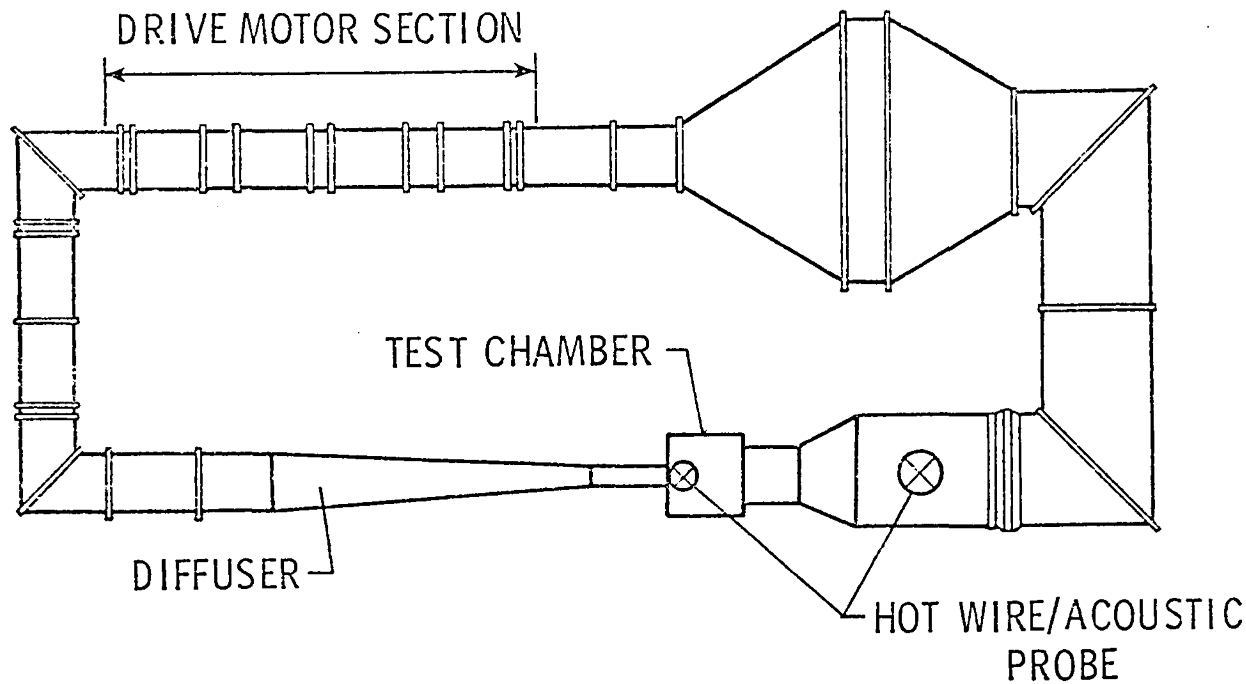



Figure 1.- Schematic of the Ames 2x2 Ft. Transonic Wind Tunnel and Probe Locations.

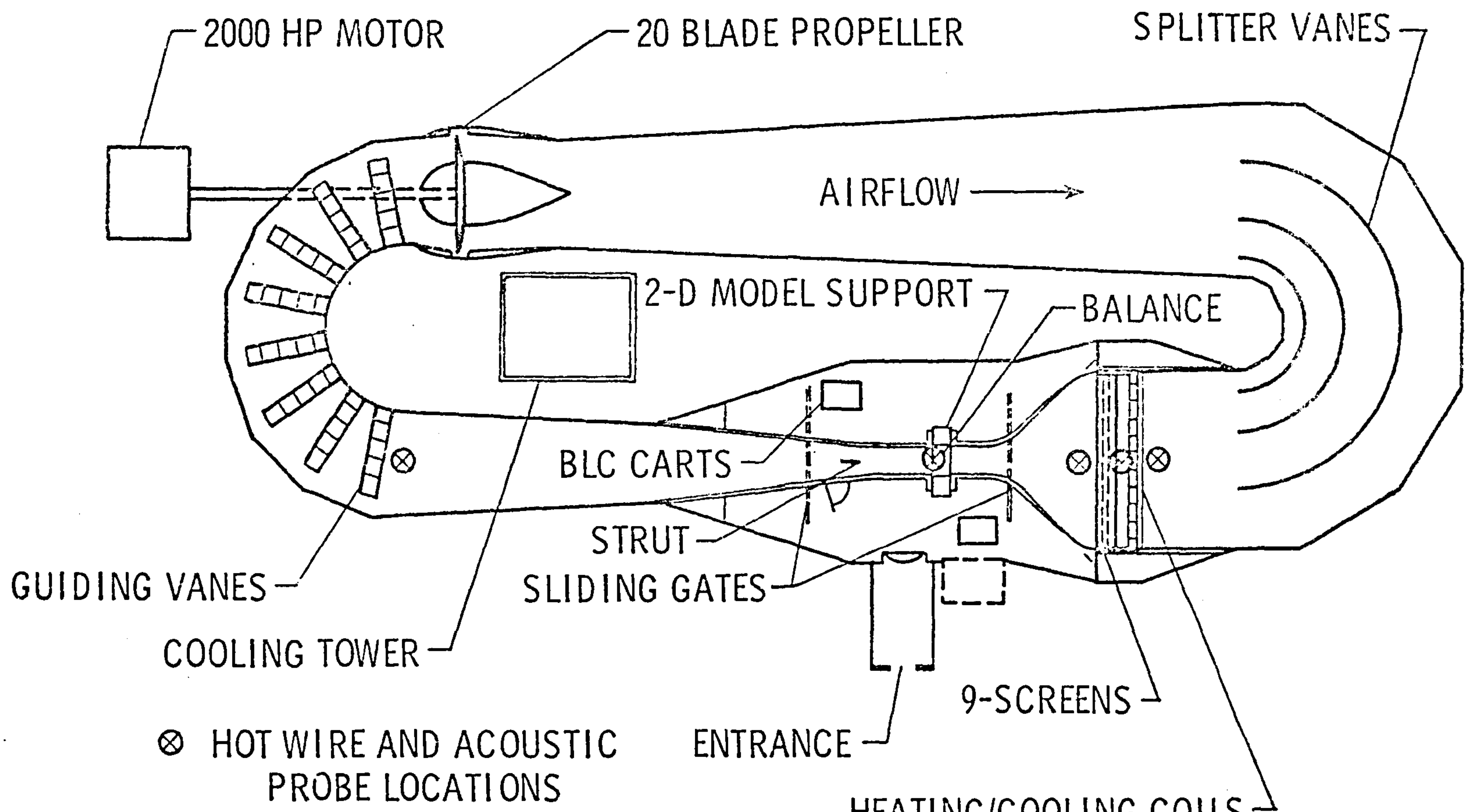



Figure 2.- Schematic of the Low-Turbulence Pressure Tunnel and Probe Locations.

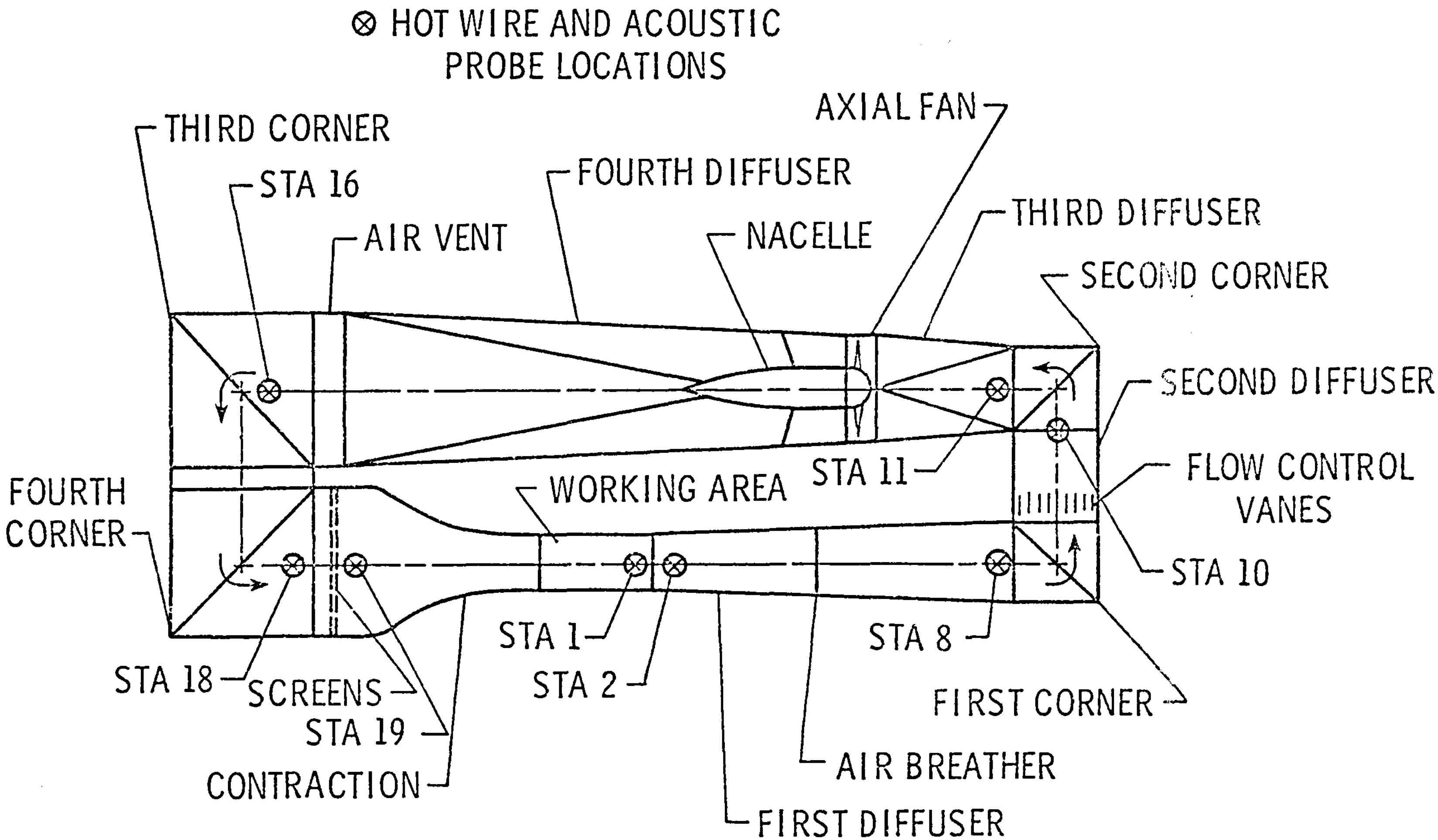
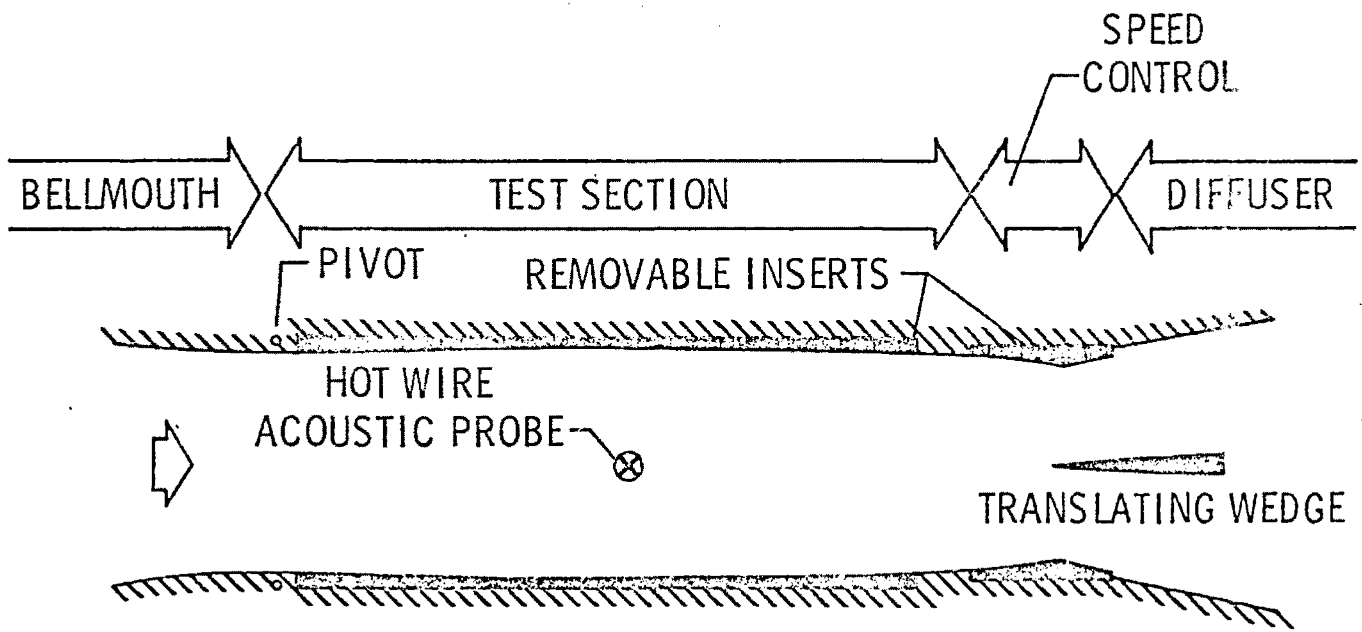
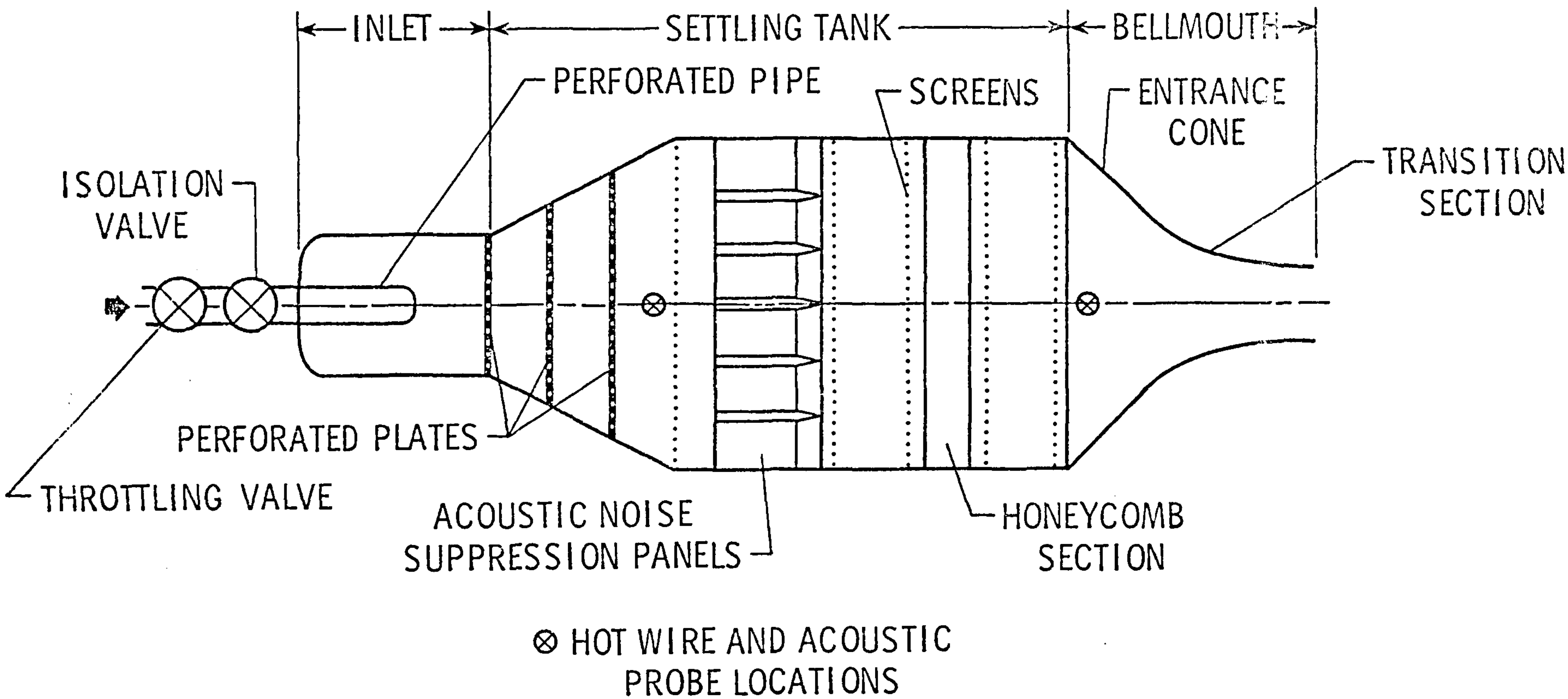



Figure 3.- Schematic of the Langley 4x7 Meter Wind Tunnel and Probe Locations.




(a) Test section

Figure 4.- Schematic of Ames High Reynolds Number Channel-1 Wind Tunnel and Probe Location.




(b) Flow conditioning tank

Figure 4.- Concluded.

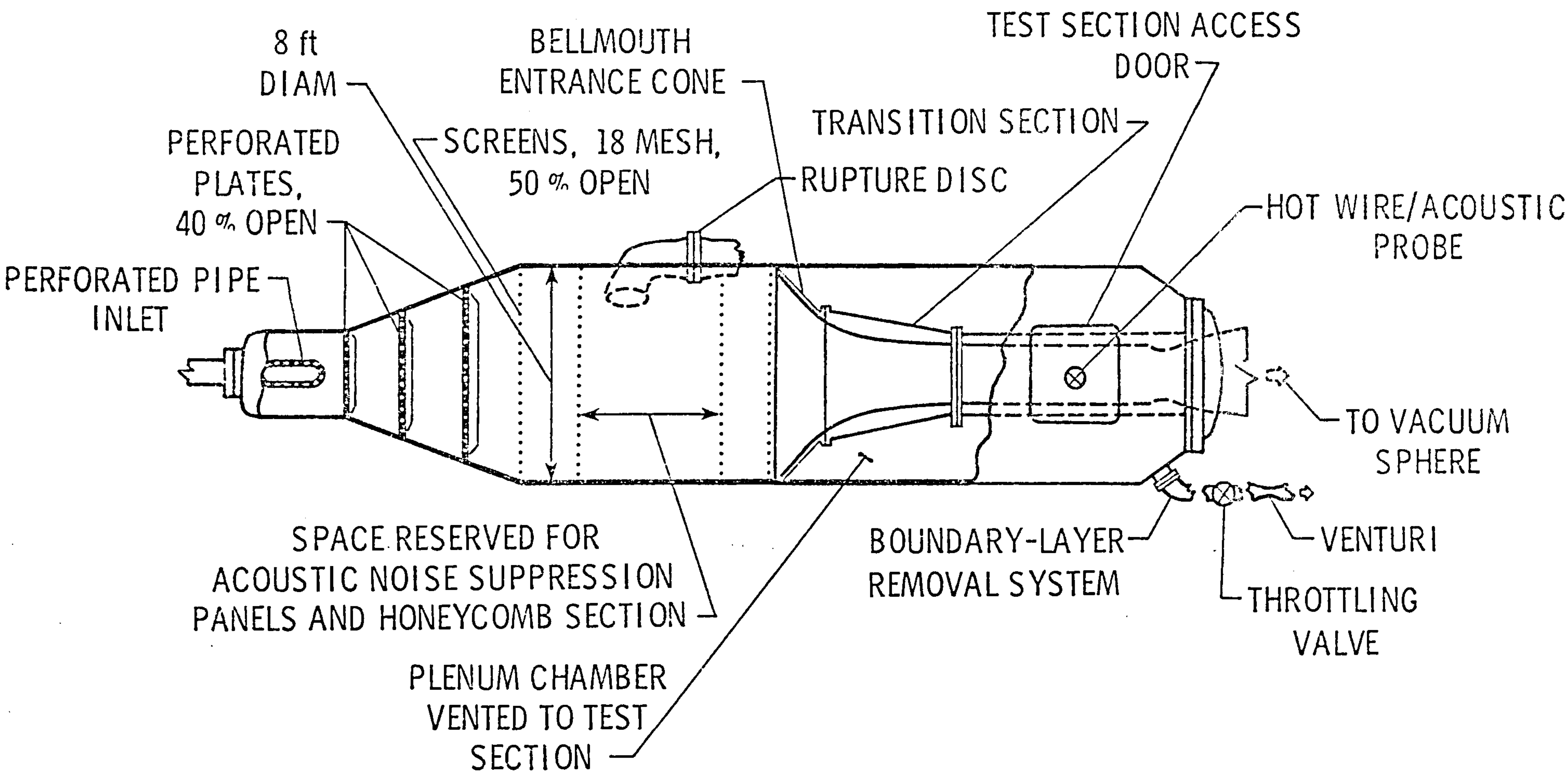



Figure 5.- Schematic of Ames High Reynolds Number Channel-2 Wind Tunnel and Probe Location.

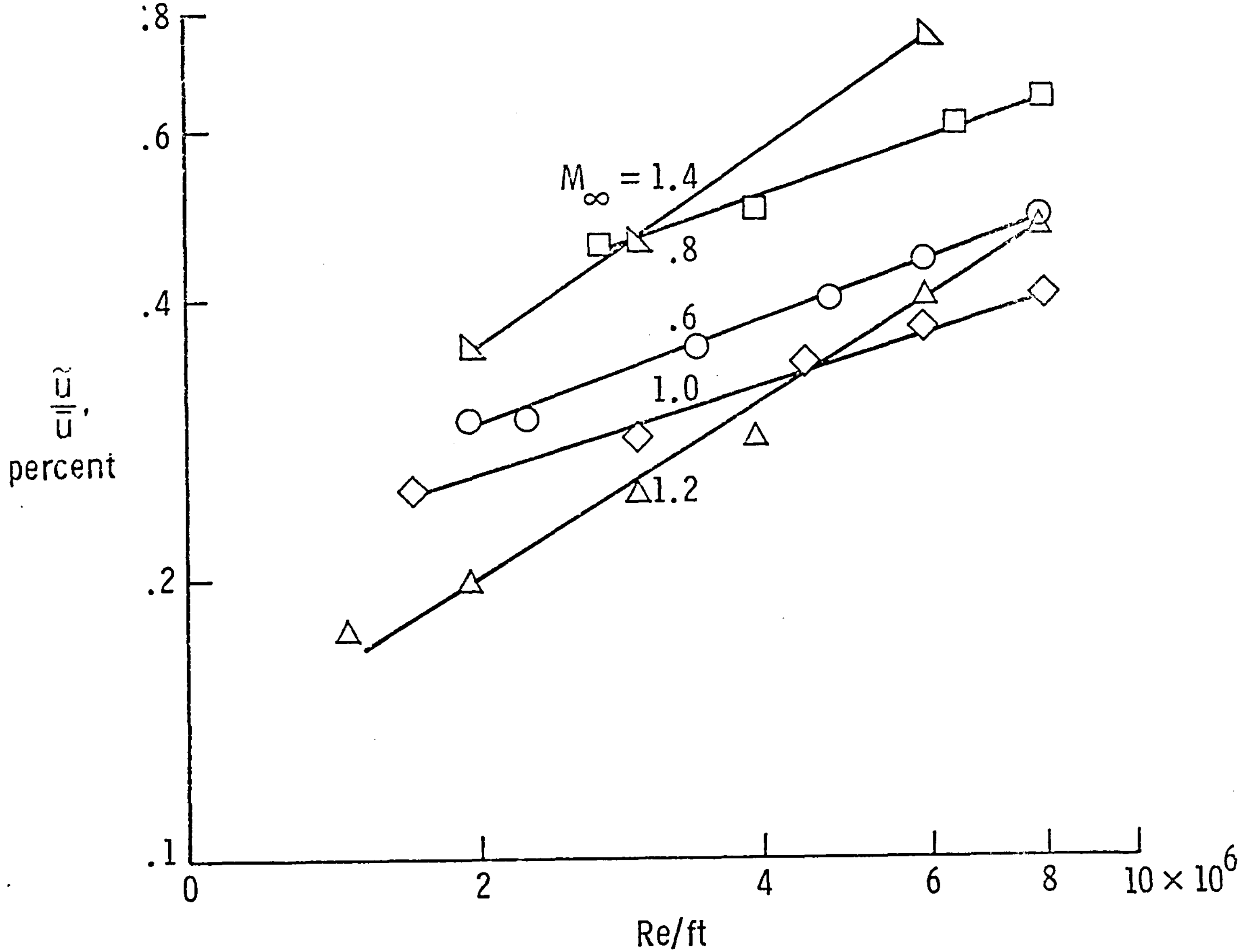



Figure 6.- Free stream pressure fluctuation levels in the Ames 2x2 Ft. Transonic Wind Tunnel.

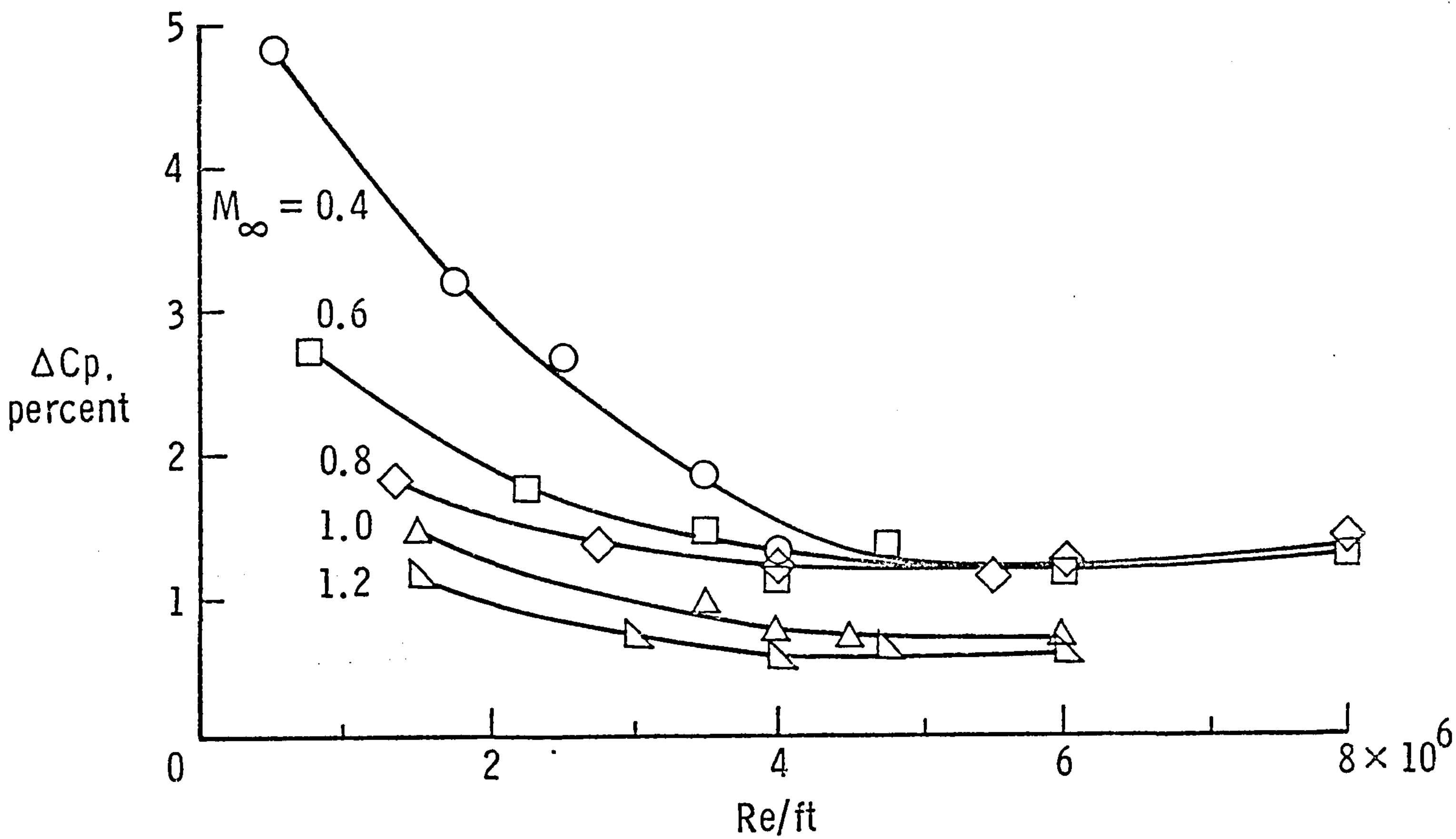



Figure 7.- Free-stream pressure fluctuation levels in the Ames 2x2 Ft. Transonic Wind Tunnel.

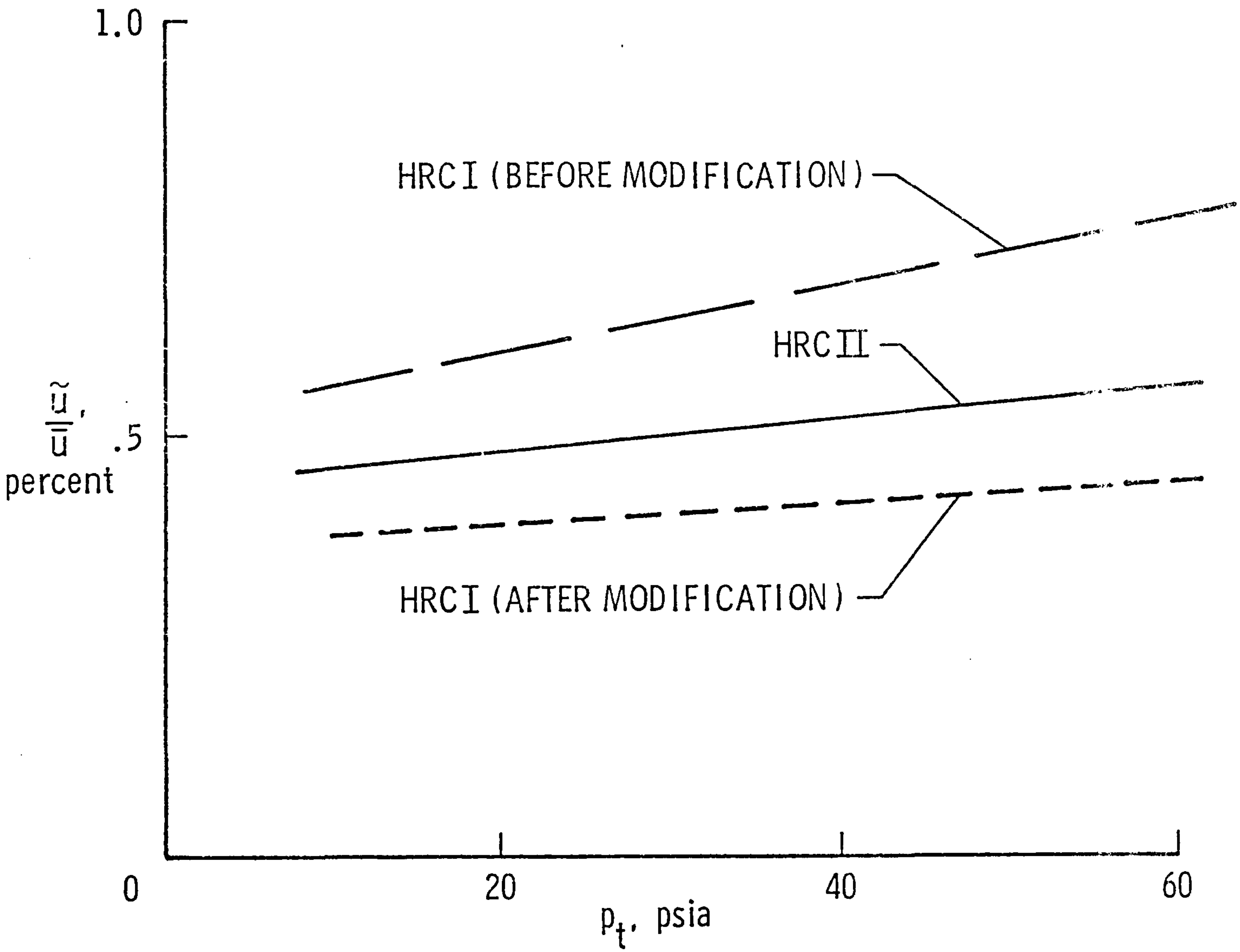



Figure 8.- Comparison of velocity fluctuation levels measured in the Ames High Reynolds Number Channel-I and II, $M_\infty = 0.8$.

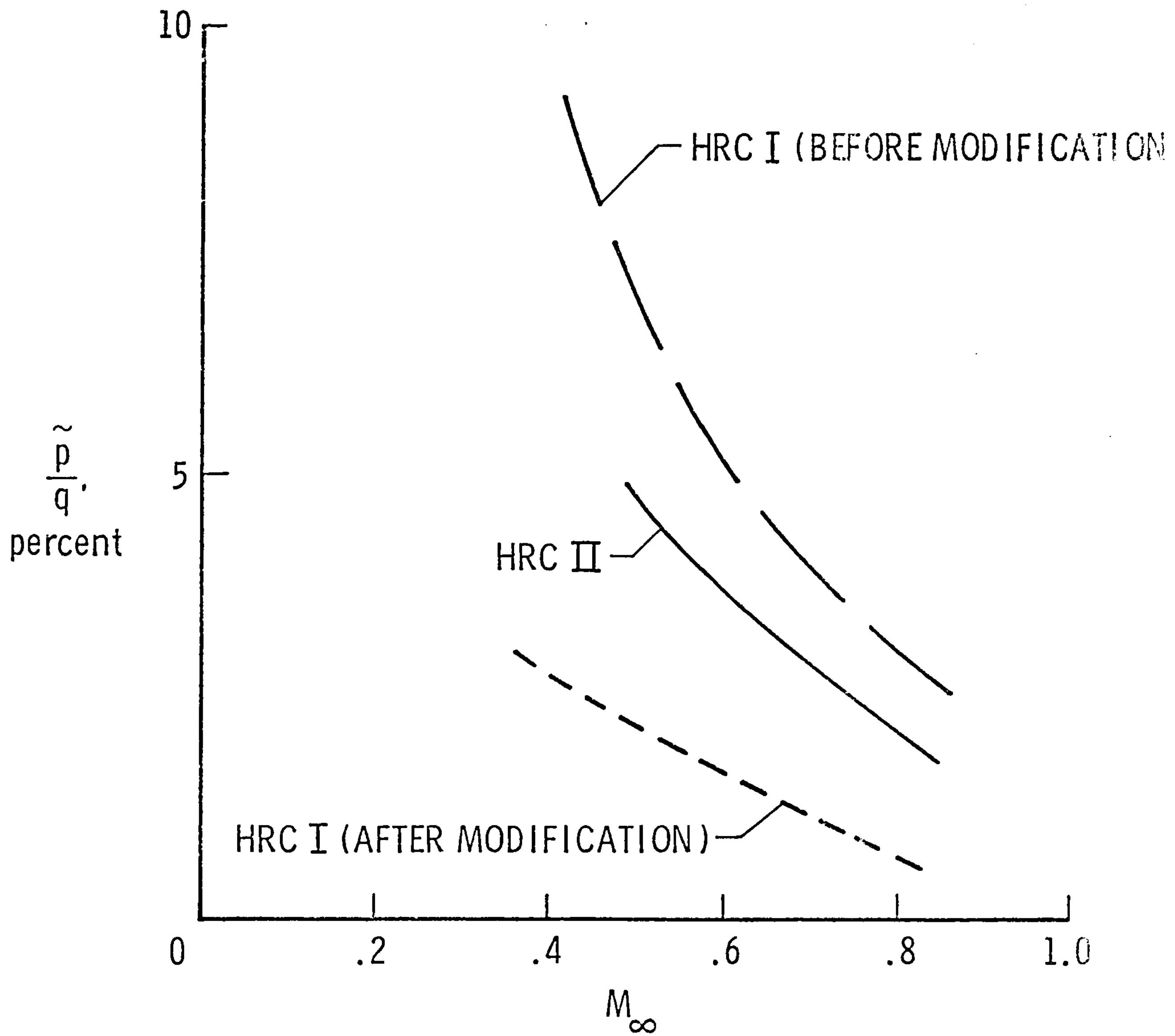



Figure 9.- Comparison of pressure fluctuation levels measured in the Ames High Reynolds Number Channel-1 and II, $M_\infty = 0.8$.

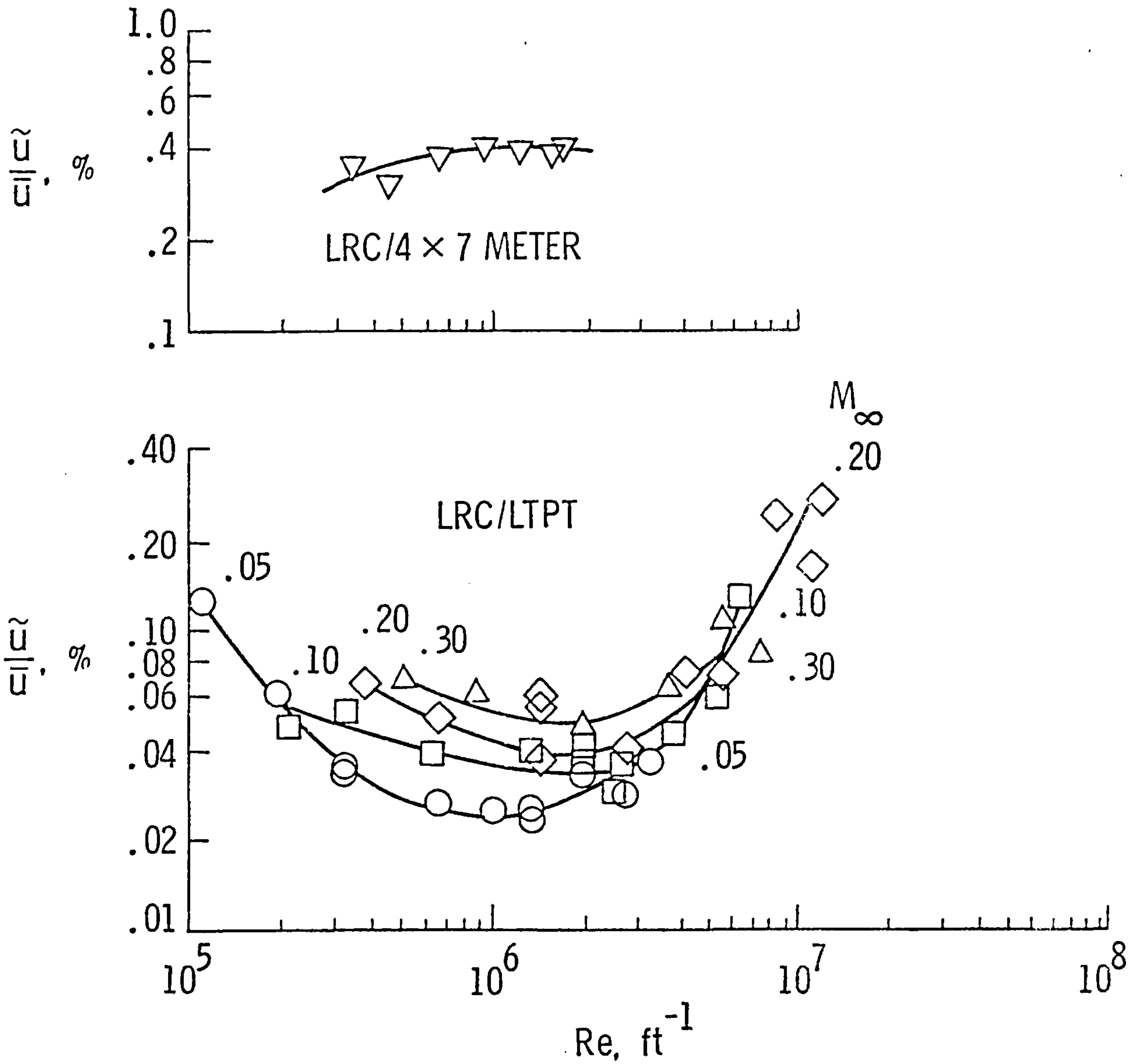



Figure 10.- Comparison of turbulence levels measured in the test section of the LaRC/4x7 Meter Tunnel and LaRC/Low Turbulence Pressure Tunnel.

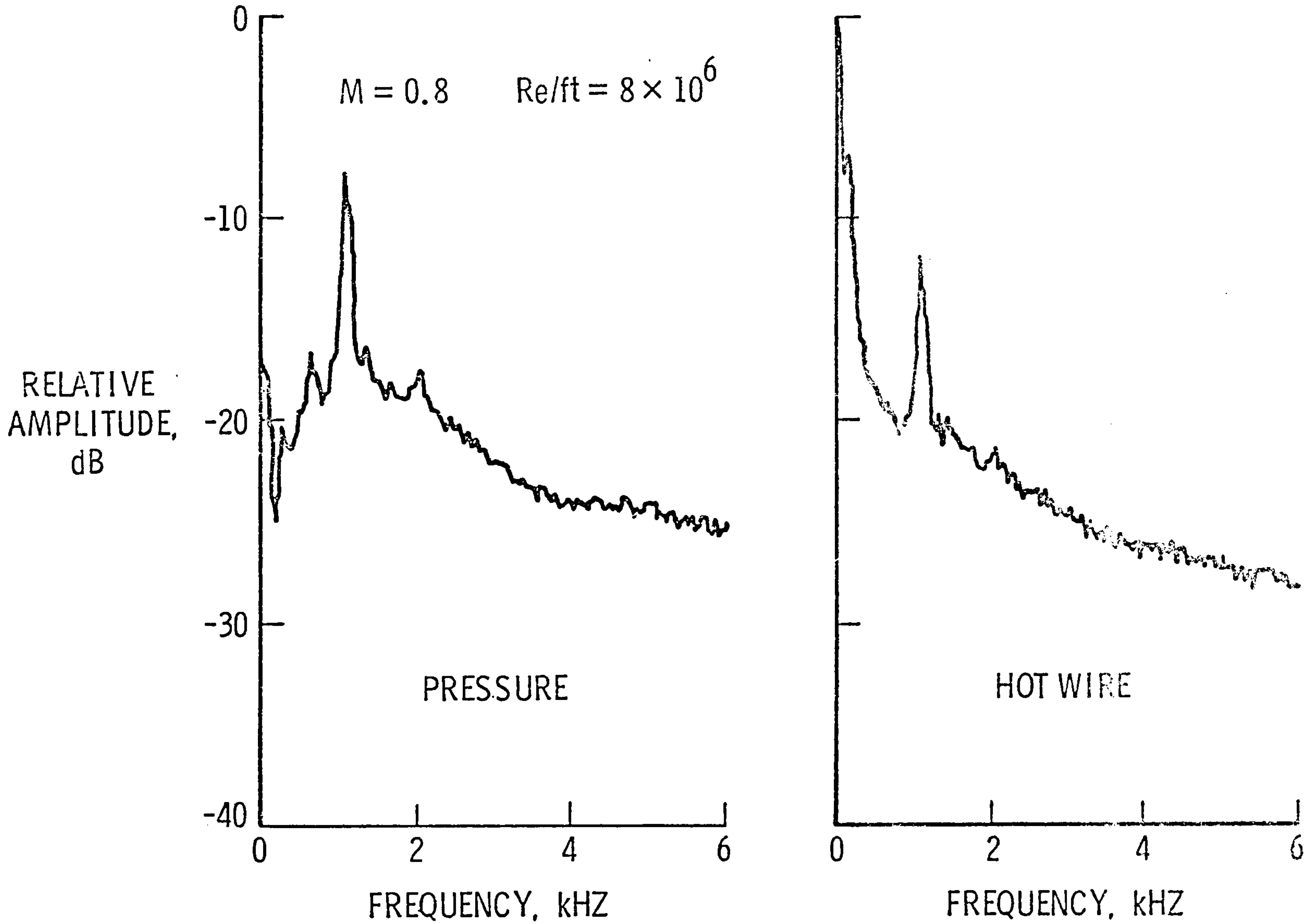



Figure 11.- Comparison of measured free-stream spectra in the Ames 2x2 Ft. Transonic Pressure Tunnel test section using acoustic and hot wire probes.

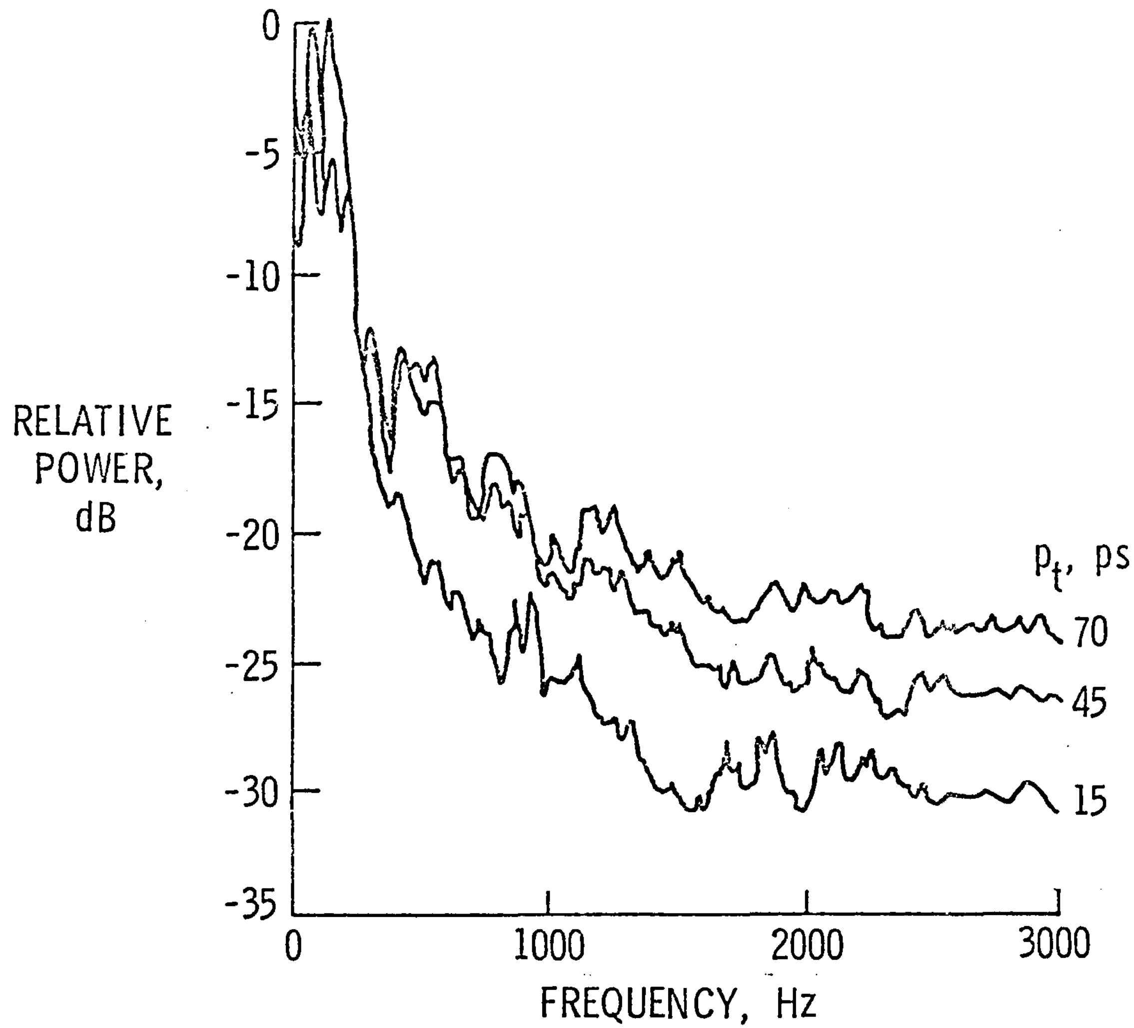



Figure 12.- Measured free-stream spectra in the Ames High Reynolds Number Channel-I Wind Tunnel.

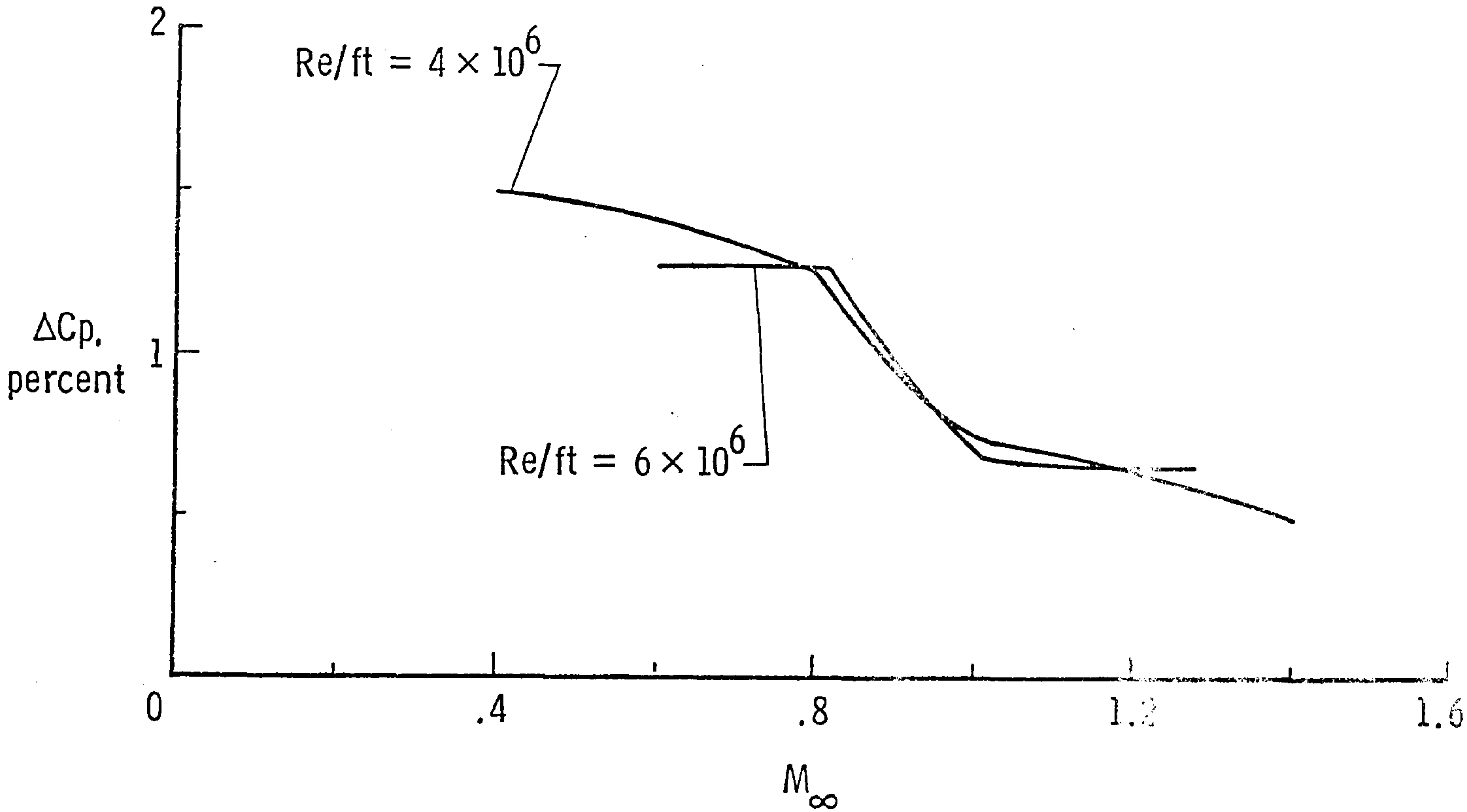



Figure 13.- Free-stream dynamic pressure variations measured in the Ames 2x2 Ft. Transonic Pressure Tunnel.

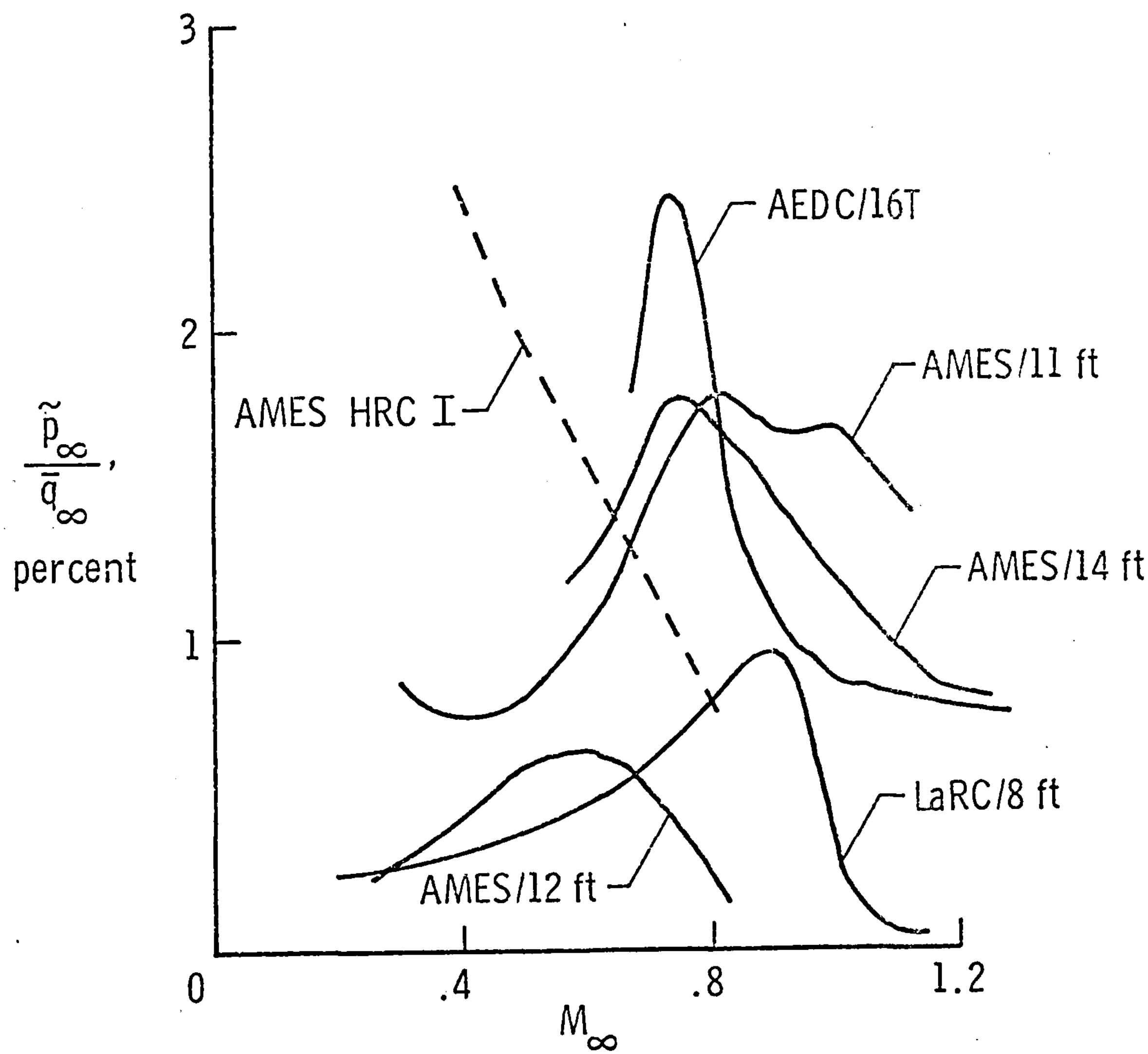



Figure 14.- Comparison of measured pressure fluctuation levels on the test section centerline of several transonic wind tunnels.

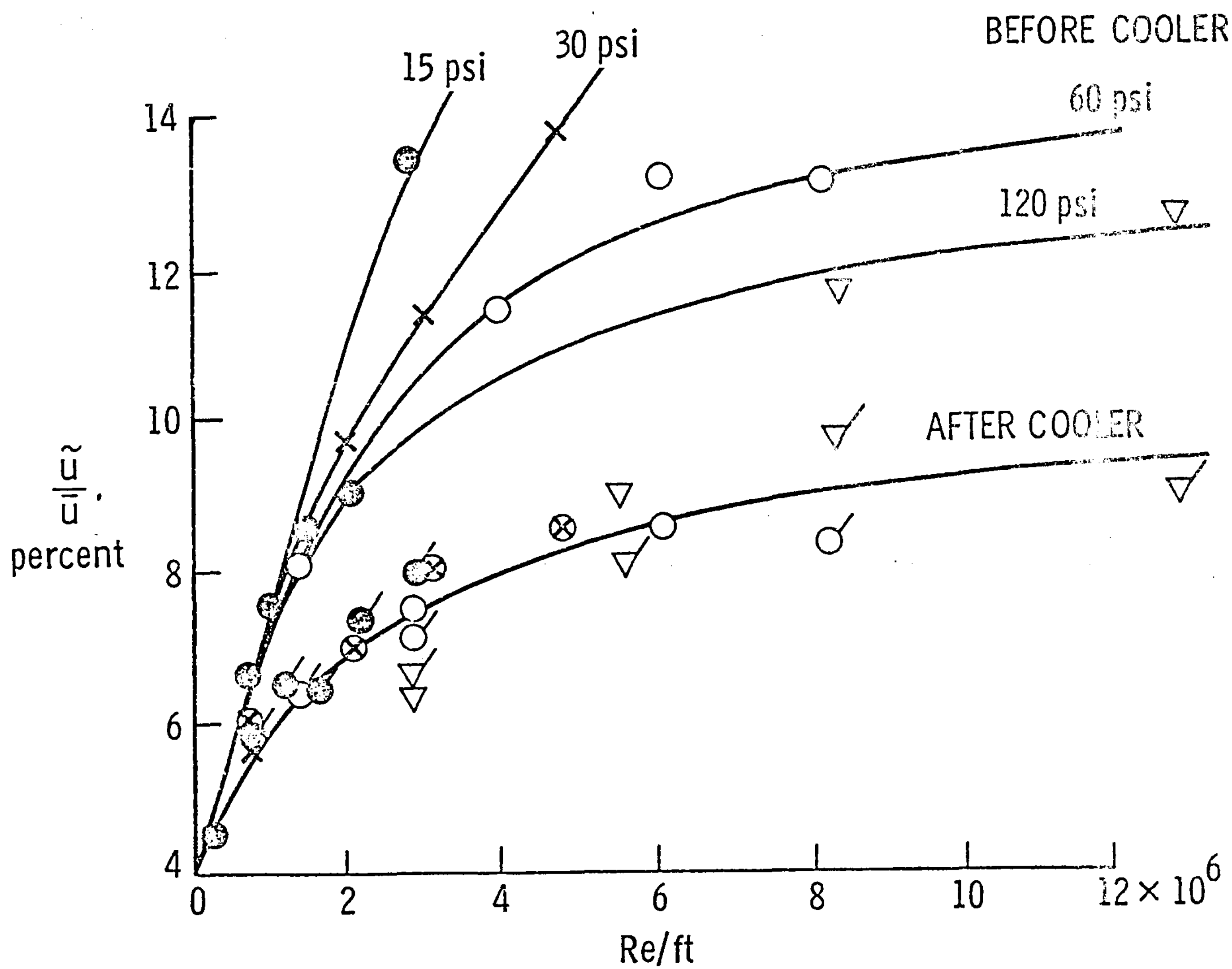



Figure 15.- Turbulence level measurements across the cooler in the Langley Low Turbulence Pressure Tunnel.

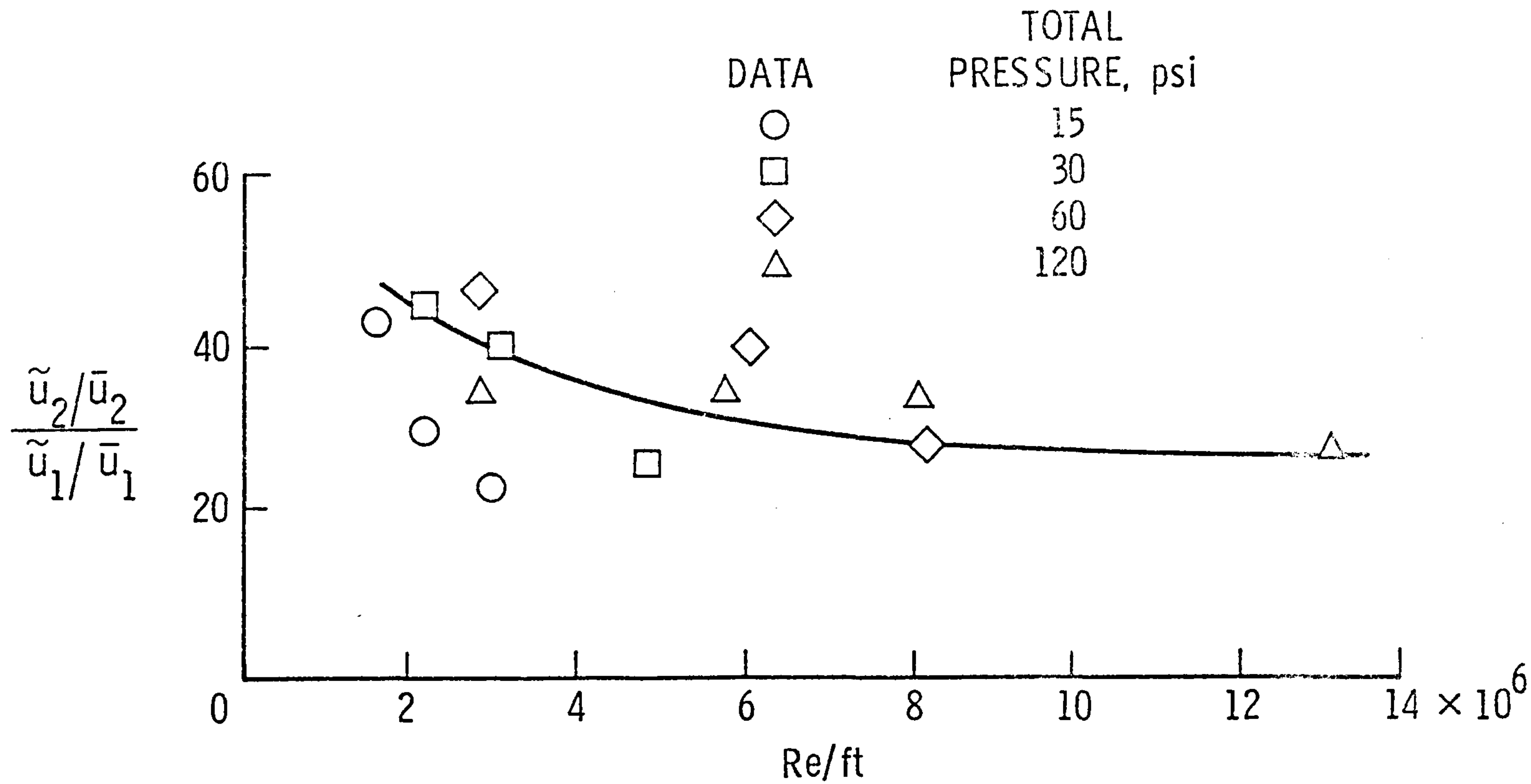



Figure 16.- Turbulence reduction measured across screens in settling chamber of Langley Low Turbulence Pressure Tunnel.

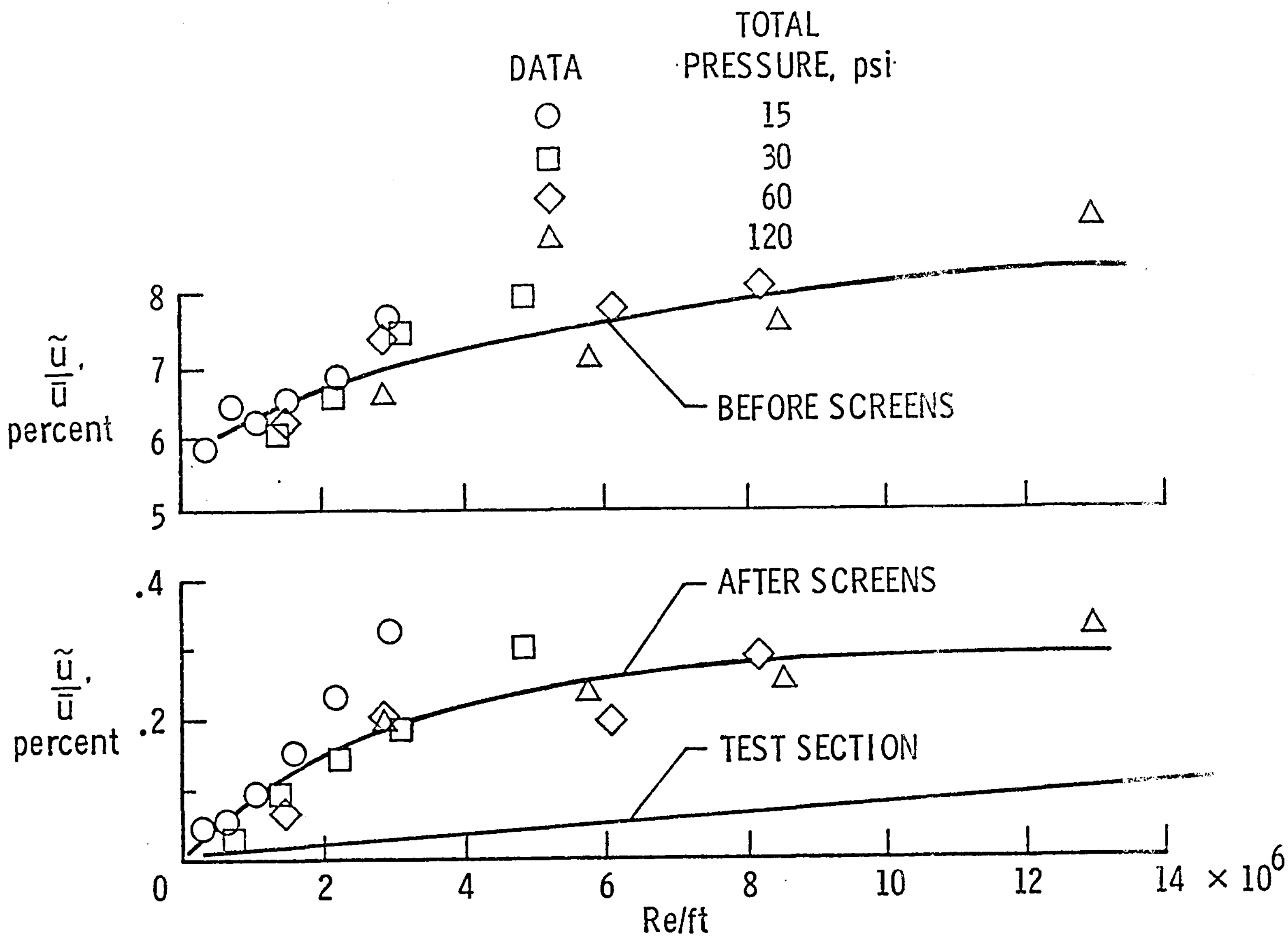



Figure 17.- Comparison of turbulence measurements before and after the screens with that in LaRC/Low Turbulence Pressure Tunnel test section.

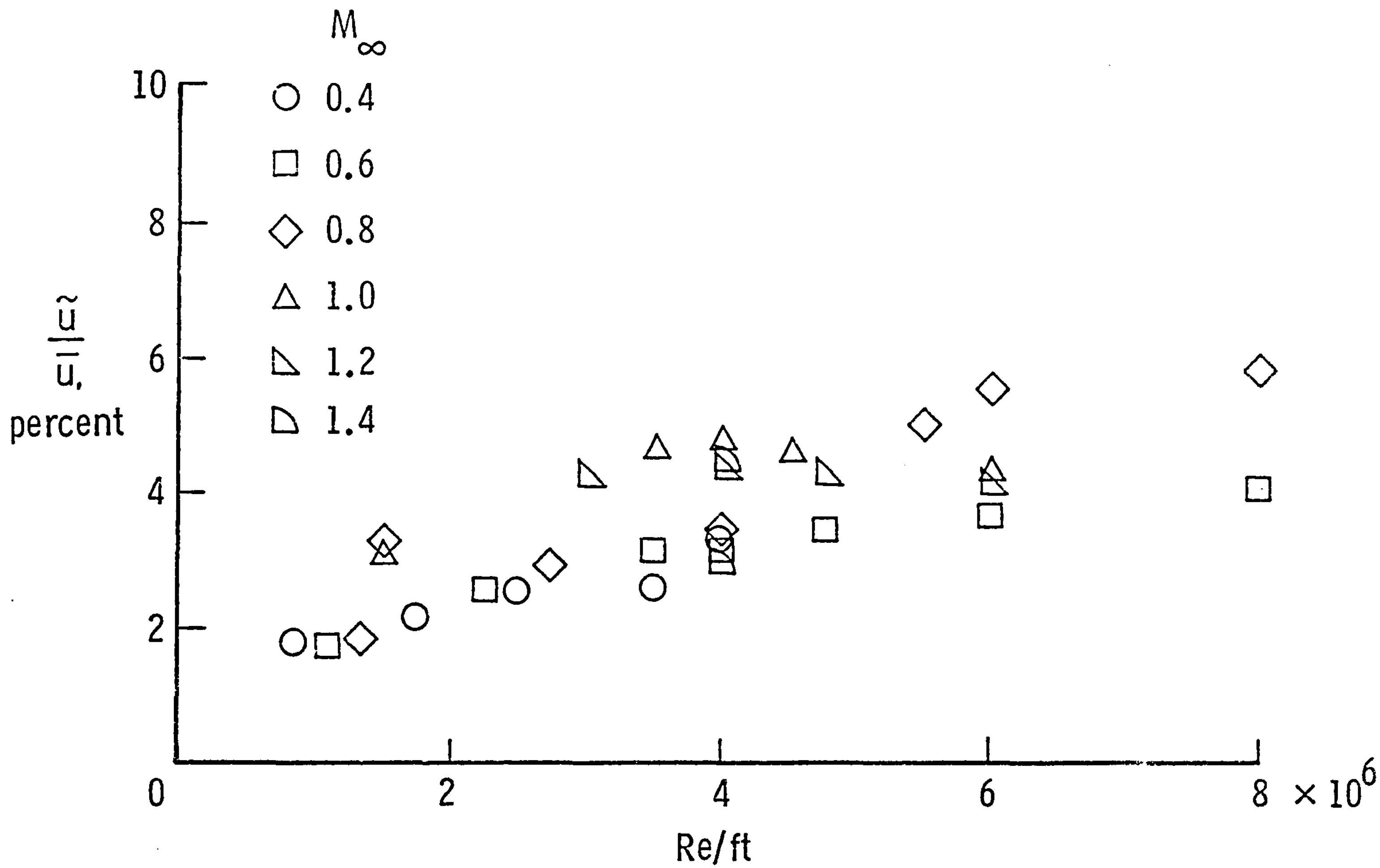



Figure 18.- Measured settling chamber turbulence level in the Ames 2x2 Ft. Transonic Pressure Tunnel.

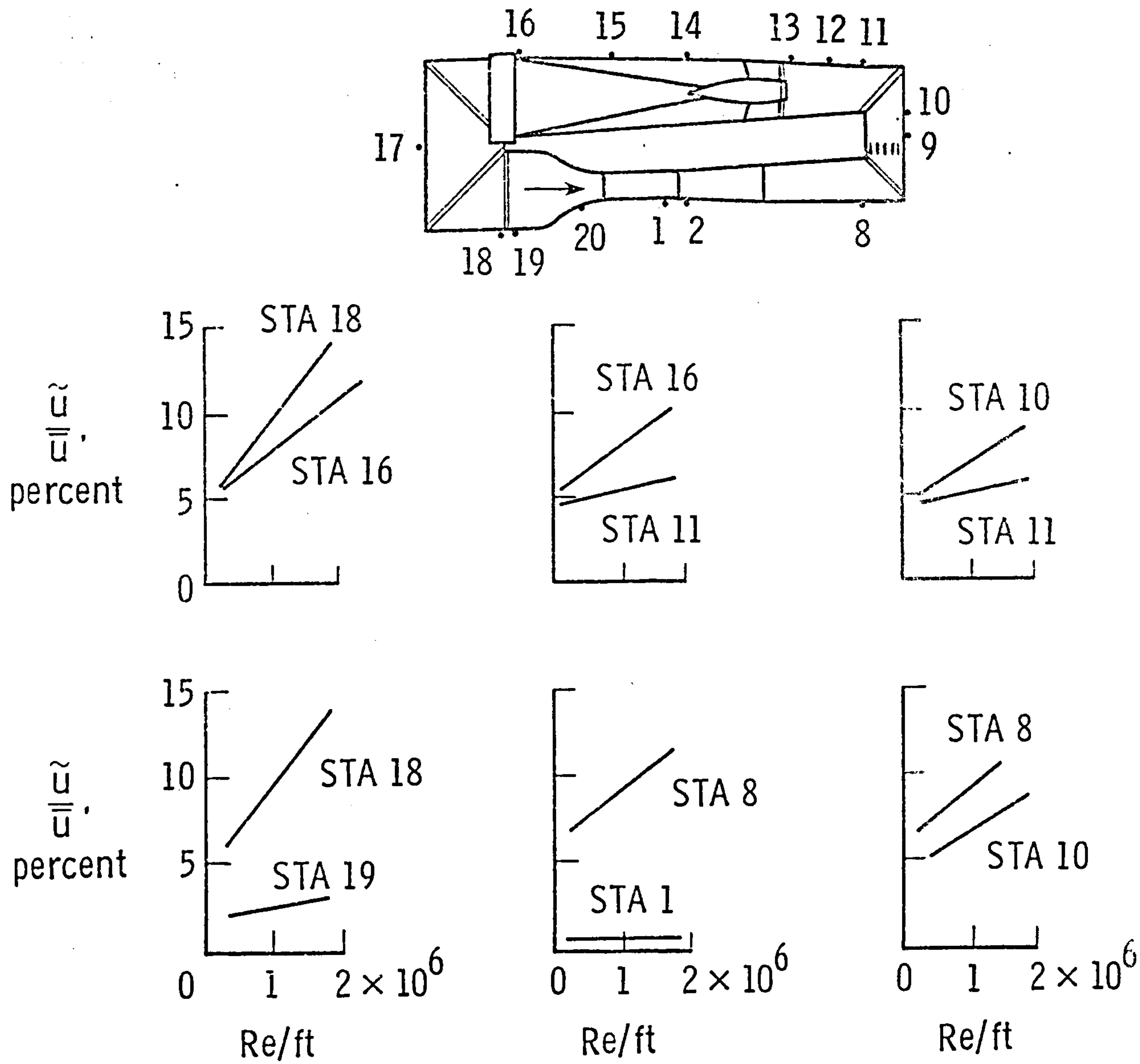



Figure 19.- Turbulence levels measured around the circuit of the Langley 4x7 Meter Wind Tunnel.

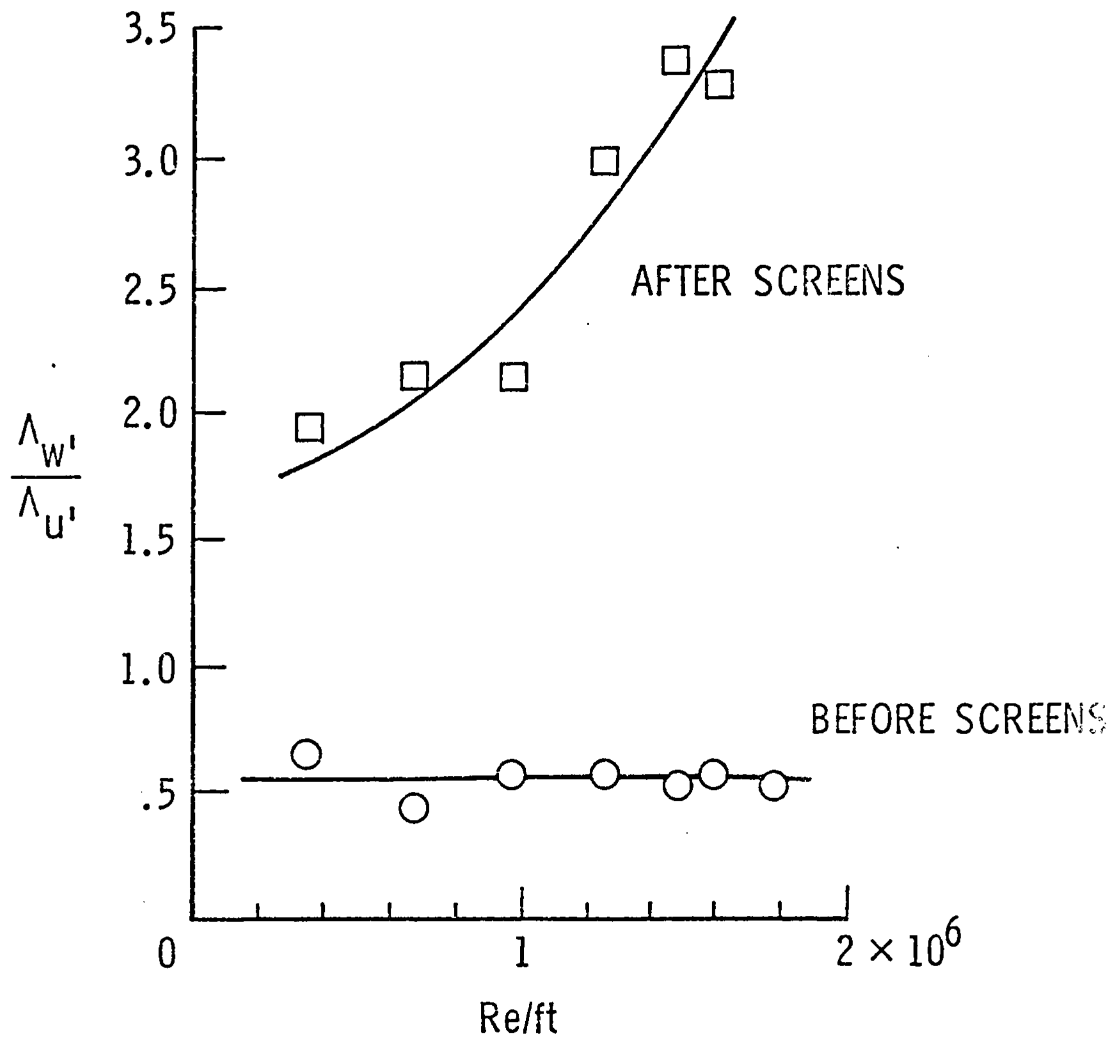



Figure 20.- Turbulence scale measurements across the settling chamber screens in the Langley 4x7 Meter Wind Tunnel.

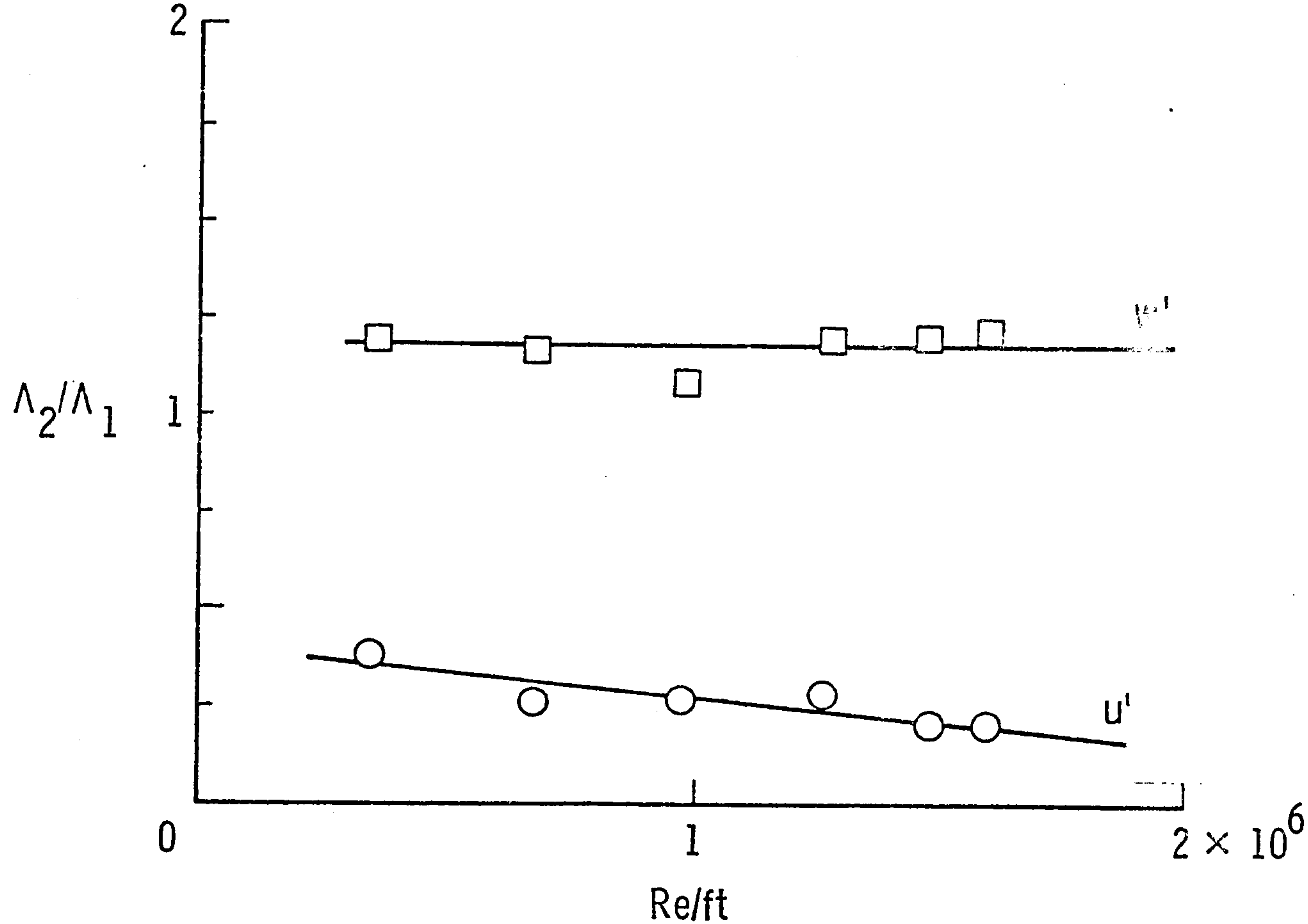



**Figure 21.- Effect of screens on integral scale ratios in the Langley 4x7 Meter Wind Tunnel.**

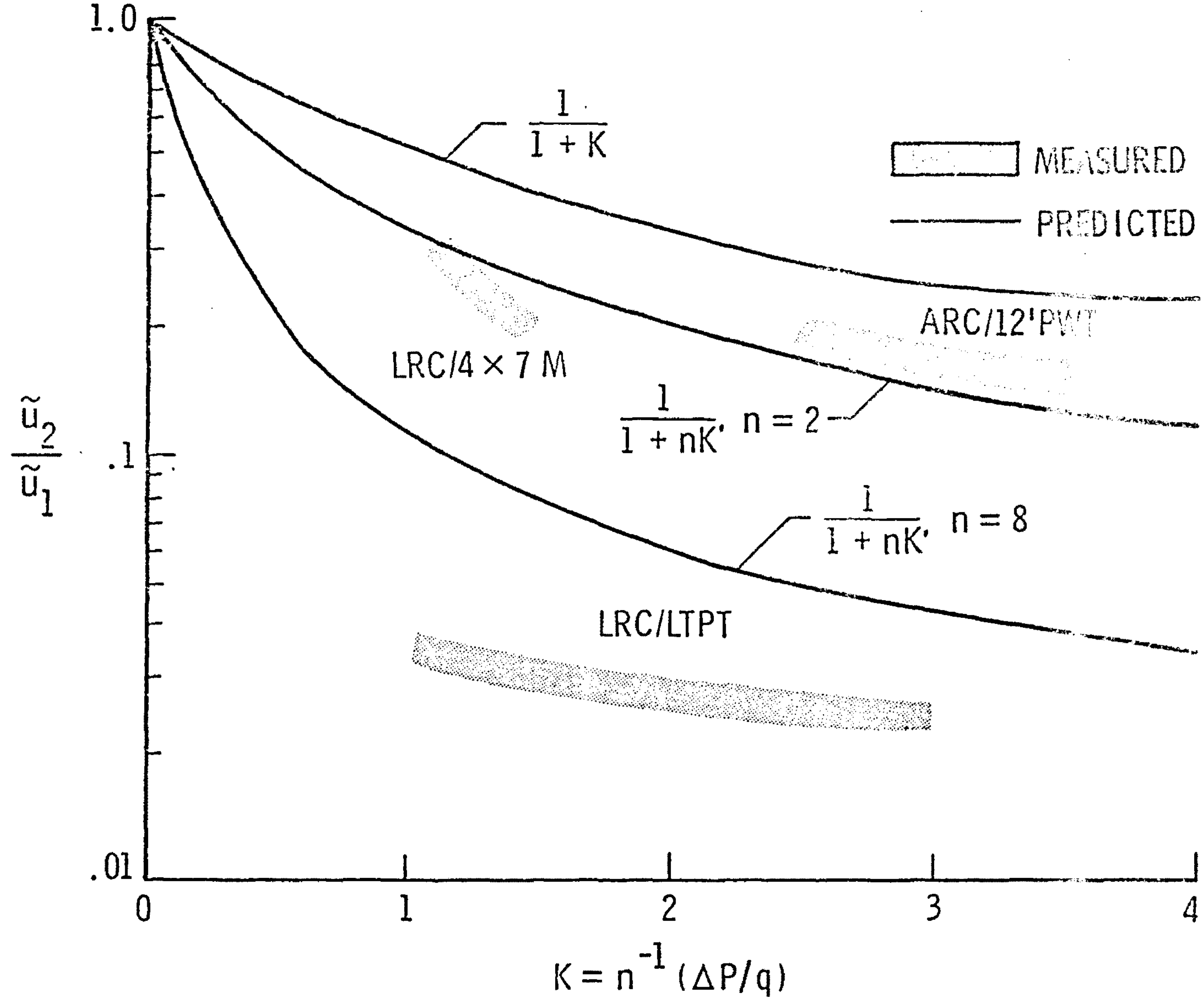



Figure 22.- Comparison of screen effectiveness in the ARC/12-Ft. Pressure Wind Tunnel, LaRC/4x7Meter Tunnel, and LaRC/Low Turbulence Pressure Tunnel.

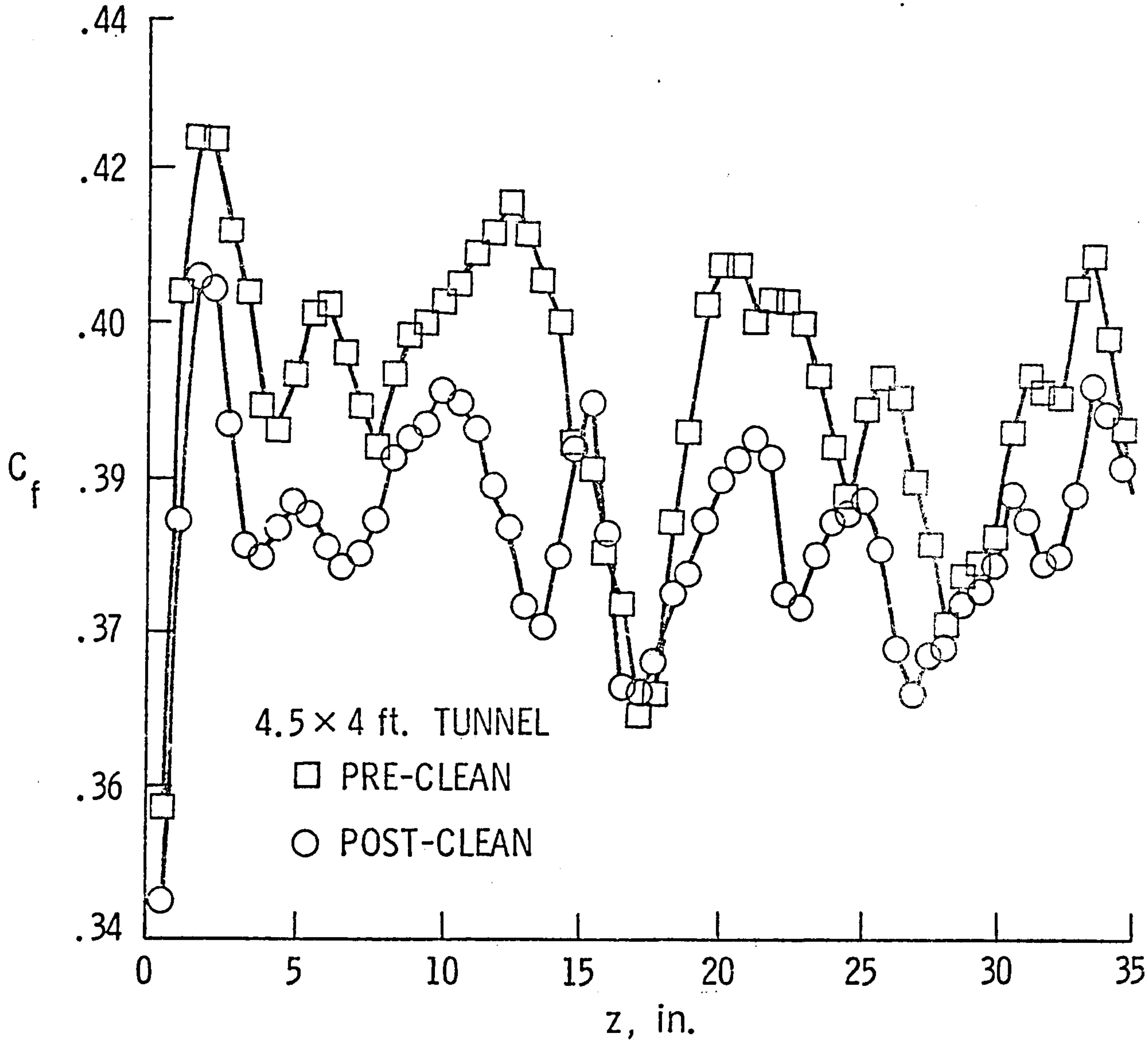



Figure 23.- Spanwise skin-friction distribution on the RAE 4.5x4 Ft. (ref. 14) working section floor before and after cleaning the last screen in the settling chamber.

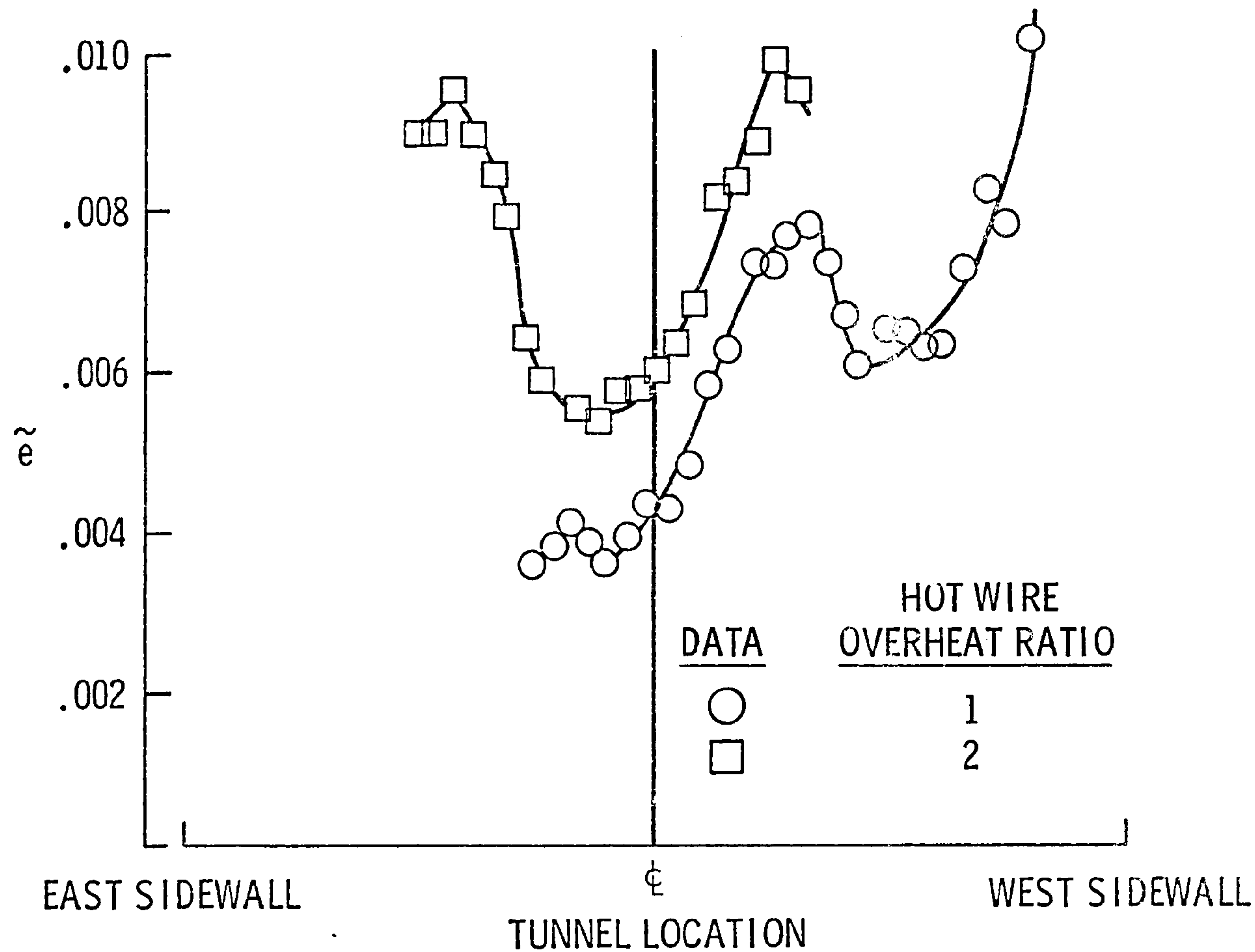



Figure 24.- Measured hot wire rms voltage variations across the test section of the Ames 2x2 Ft. Transonic Pressure Tunnel with different wire sensitivities.

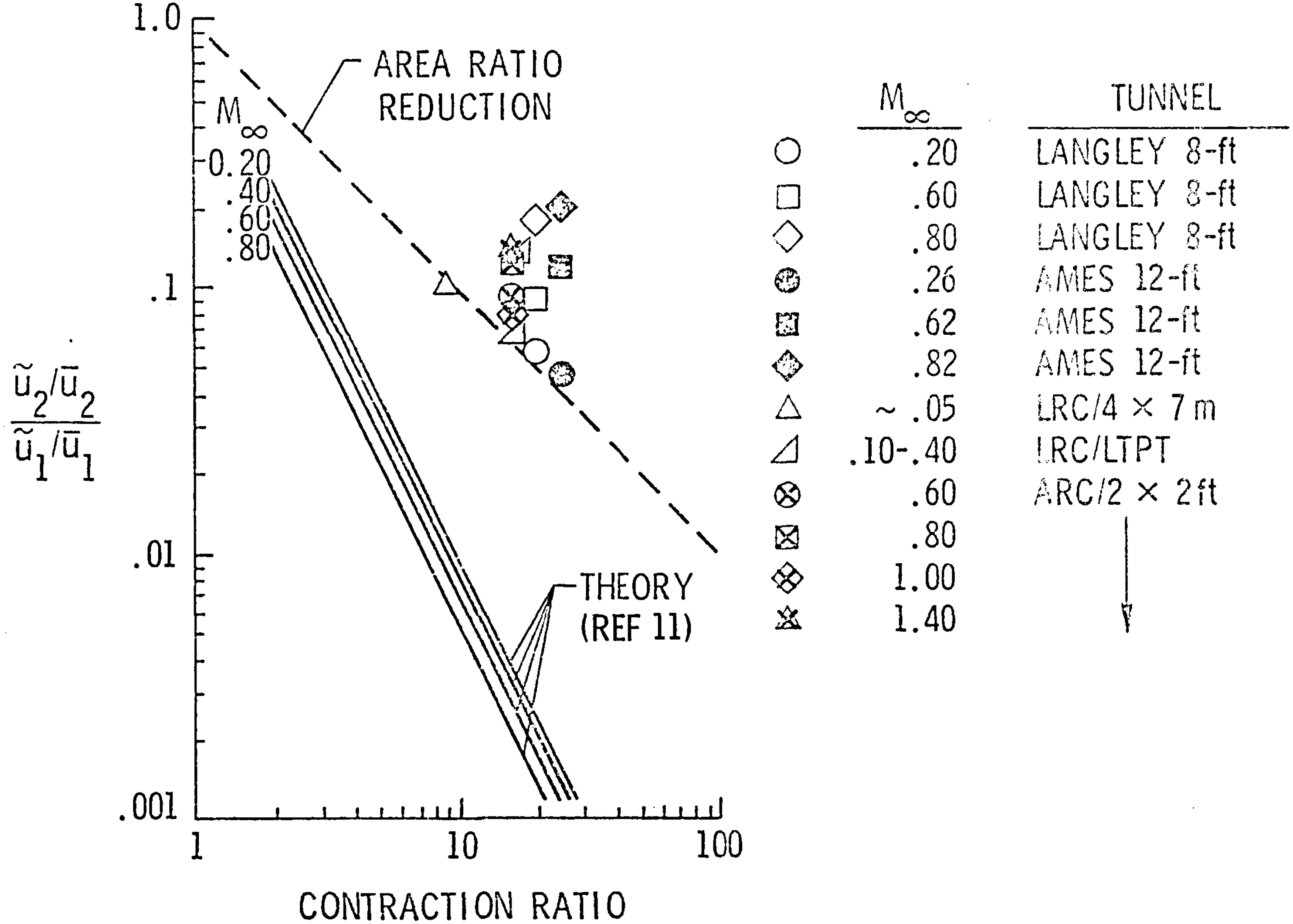



Figure 25.- Effect of nozzle contraction on turbulence transmissibility in wind tunnels compared with theory.

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA TM-85659 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| An Evaluation and Assessment of Flow Quality in Selected NASA Wind Tunnels | August 1983 |
| | 6. Performing Organization Code<br>505-31-53-09 |
| 7. Author(s)<br>W. D. Harvey, P. C. Stainback, and F. K. Owen* | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>NASA Langley Research Center<br>Hampton, VA 23665 | 10. Work Unit No. |
| | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, DC 20546 | 13. Type of Report and Period Covered<br>Technical Memorandum |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes
*Consultant, Complere Inc.
Post Office Box 1697
Palo Alto, CA 94302

16. Abstract

Tests have been conducted in a number of NASA wind tunnels to measure disturbance levels and spectra in their respective settling chambers, test sections, and diffusers to determine the sources of their disturbances. The present data supplements previous results in other NASA tunnels and adds to the ongoing acquisition of a disturbance level data base. The present results also serve to explain flow related sources which cause relatively large disturbance amplitudes at discrete frequencies. The installation of honeycomb, screens, and acoustic baffles in or upstream of the settling chamber can significantly reduce the disturbance levels.

| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
|---|---|
| Flow Quality<br>Turbulence<br>Flow Noise<br>Fluid Dynamics<br>Aerodynamics | Unclassified - Unlimited<br><br>Subject Category 02 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 45 | A03 |

N-305